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Report to the International Joint Commission on the Pollution of Lake Erie, Lake Ontario and the International Section of the St. Lawrence River: Volume 2 Lake Erie

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2

POLLUTION OF LAKE ERIE, LAKE ONTARIO AND THE INTERNATIONAL SECTION OF THE ST. LAWRENCE RIVER

Volume 2—Lake Erie

BY THE
INTERNATIONAL LAKE ERIE WATER POLLUTION BOARD,
AND THE
INTERNATIONAL LAKE ONTARIO—ST. LAWRENCE RIVER
WATER POLLUTION BOARD. 1969

report to the INTERNATIONAL JOINT COMMISSION on the

POLLUTION OF LAKE ERIE

Volume 2

BY THE
INTERNATIONAL LAKE ERIE WATER POLLUTION BOARD
AND THE
INTERNATIONAL LAKE ONTARIO - ST. LAWRENCE RIVER
WATER POLLUTION BOARD
1969.

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Volume 2

Lake Erie

Chapter 4. DEVELOPING PROBLEMS

Chapter 5. CONCLUSIONS AND SUMMARY

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INTRODUCTION

The first comprehenisve report on pollution of boundary waters was issued by the International Joint Commission in 1918[1] following investigations from 1913 to 1916. The section of that report dealing with water pollution problems in the Great Lakes area, though concerning itself primarily with the Connecting Channels (St. Clair River, Lake St. Clair, Detroit River, and Niagara River) did examine the quality of waters in both the western and eastern ends of Lake Erie and Lake Ontario, and in the international section of the St. Lawrence River. Subsequently, in its 1950 report[2], the Commission re-examined the problem of pollution in these waters based on studies undertaken from 1946 to 1948.

Pollution problems have changed materially over the period of study from 1913 to the present. The 1913 investigations were almost solely concerned with bacterial pollution from domestic sewage, a reflection of the few municipal sewage treatment plants then in existence. Industrial pollutants were not discharged in sufficient quantities to seriously affect water uses. The investigations showed that the open waters of Lakes Erie and Ontario were essentially free of bacterial pollution except for the western basin of Lake Erie near the mouth of the Detroit River and Lake Ontario near the mouth of the Niagara River. Bacterial pollution on a localized scale in nearshore waters did, however, constitute a direct threat to municipal water supplies.

The report of 1950 indicated that many of the municipalities identified in the earlier report had constructed sewage treatment works and water filtration plants to ensure safe water supplies. However, the extension of sewer services and the installation of treatment plants for domestic wastes had not kept up with growth in the area. The economic, industrial and agricultural expansion which took place from 1913 to 1946 resulted in major increases of sewage discharges and new wastes. Industrial pollution which was not considered to be a problem in 1913 was recognized as a growing problem in 1948.

Control programs to combat the bacterial pollution reported in the 1918 study and to provide the treatment recommended in the 1950 report were not adequate to keep pace with the problems arising from continued urban and industrial expansion in the lower lakes basins. Changes in manufacturing processes and commodity use had caused new and widespread

[1]Final report of the International Joint Commission on the Pollution of Boundary Waters Reference, August, 1918.

[2]Report of the International Joint Commission on the Pollution of Boundary Waters, October, 1950.

pollution problems, while bacterial pollution continued in evidence despite the fact that many of the major sources were controlled. The urban and industrial complexes in the lower lakes basins were developed without adequate knowledge of the effects of multiple releases of wastes to water. Further, many resource materials were discharged into the lakes because ignorance existed of ways and means to convert these materials to economic benefit. In other cases materials recovery systems were either inadequate or poorly operated.

On October 7, 1964, the Governments of the United States and Canada informed the International Joint Commission that they had reason to believe the waters of Lake Erie, Lake Ontario and the international section of the St. Lawrence River were being polluted by sewage and industrial wastes, and accordingly had "agreed upon a joint reference of the matter" to the Commission pursuant to the provisions of Article IX of the Boundary Waters Treaty of 1909.

The Commission was requested to inquire into and report to the two governments as soon as practicable upon the following questions:

1. are the waters of Lake Erie, Lake Ontario, and the international section of the St. Lawrence River being polluted on either side of the boundary to an extent which is causing or is likely to cause injury to health or property on the other side of the boundary?

2. if the foregoing question is answered in the affirmative, to what extent, by what causes, and in what localities is such pollution taking place?

3. if the Commission should find that pollution of the character just referred to is taking place, what remedial measures would, in its judgment, be most practicable from the economic, sanitary and other points of view, and what would be the probable cost thereof?

In order to make the necessary investigations and studies to form the basis for its report to the Governments of the United States and Canada, the Commission established two Advisory Boards:

1. The International Lake Erie Water Pollution Board, and

2. The International Lake Ontario and St. Lawrence River Water Pollution Board.

Representatives from the Federal Governments of the two countries, and from the States of New York, Pennsylvania, Ohio, Michigan, and the Province of Ontario were appointed to these Boards.

While the two lakes, Erie and Ontario, are the smallest of the five Great Lakes, over half the population of the Great Lakes region live and work in these two basins. Thus Lake Erie and Lake Ontario have been subjected over the years to great use pressures, and have received large quantities of industrial and municipal wastes. It seems appropriate, therefore, that the first major international investigation of the Great Lakes pollution problems should be directed at these two lakes.

When the United States and Canada became signatories to the Boundary Waters Treaty, they did so in recognition of the value of protecting the boundary and transboundary waters and established an order of precedence for water use. These were (1) domestic and sanitary, (2) navigation, and (3) power and irrigation. The uses of these waters for industry, recreation and fish and wildlife purposes were not cited in the Treaty. However, they have played an increasingly important part in the development of the lakes and are recognized as uses which are entitled to full consideration along with those specifically named in the Treaty.

PROGRAM OF INVESTIGATIONS

In 1960, the Congress of the United States appropriated funds to launch a comprehensive pollution study of the Great Lakes, specifically providing for the Secretary of the Department of Health, Education and Welfare "to conduct research and technical developement work, and make studies, with respect to the quality of the waters of the Great Lakes,...."[1]. Actual studies of Lake Erie were initiated in 1963 and of Lake Ontario and the international section of the St. Lawrence River in 1964. Subsequently, through reorganization, these studies were continued by the Department of the Interior and have been used in the preparation of this report.

In Canada studies of the lower Great Lakes for this report began in 1964 after water pollution became a matter of reference to the International Joint Commission by the two governments. The Department of National Health and Welfare, the Department of Energy, Mines and Resources, the Fisheries Research Board of Canada, and the Ontario Water Resources Commission, all initiated programs to develop data on which to base recommendations for the necessary remedial actions on the two lakes.

[1]Federal Water Pollution Control Act, 1956, as amended (33 U.S.C. 466 *et seq.*).

Of considerable importance in the development of this report has been a cooperative and well-coordinated program of investigations and special studies by personnel from federal, state and provincial agencies. Other sources of pertinent data have been examined and incorporated in this report for the evaluation of long term changes.

INTERIM REPORTS

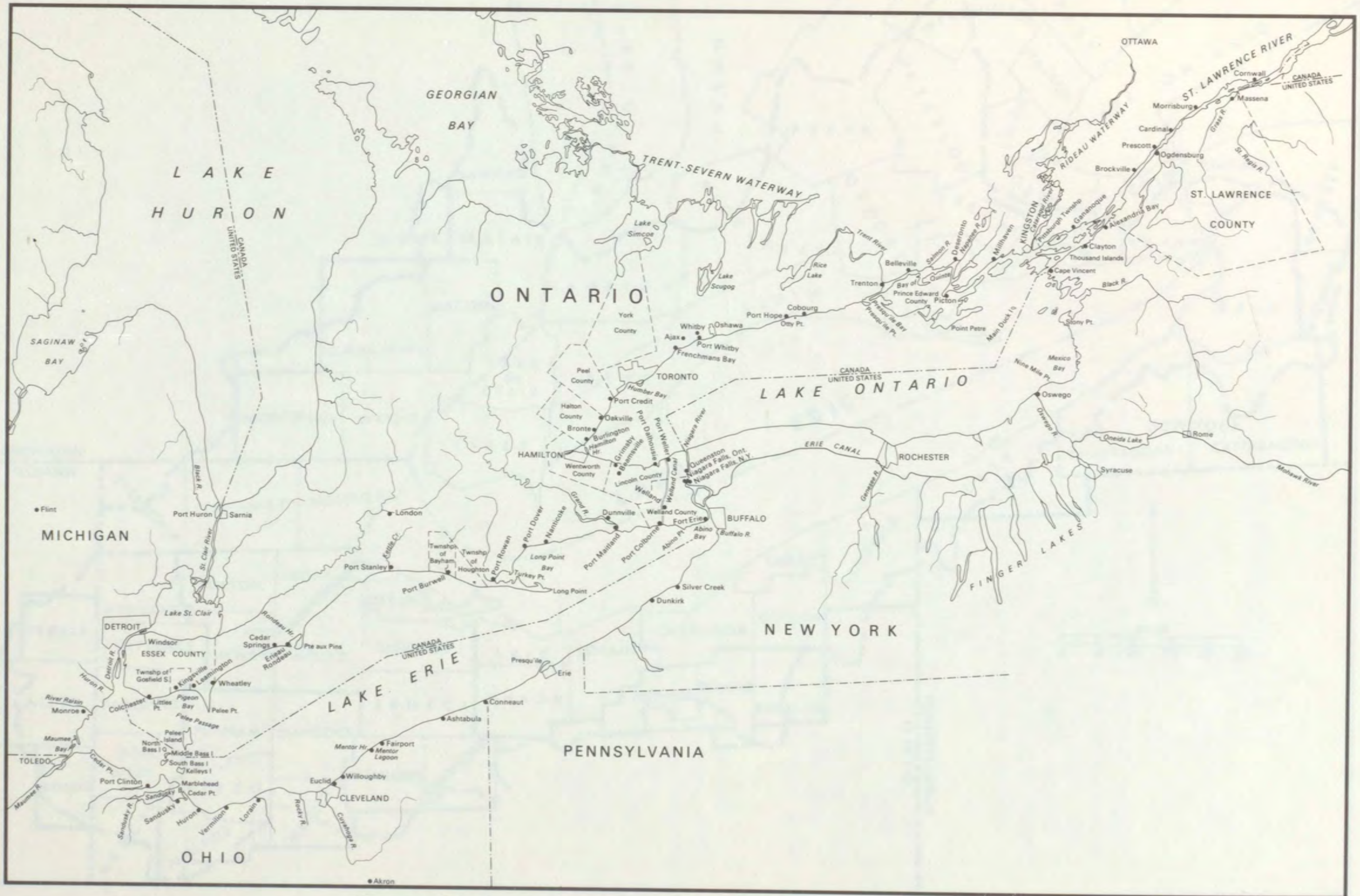
Since the work of the Advisory Boards was initiated, semi-annual reports have been submitted to the Commission to apprise it of the Boards' progress.

In September of 1965, the Boards submitted an interim report to the Commission. In that report the Boards recognized significant pollution in Lake Erie and the rapid development of similar conditions in Lake Ontario and the international section of the St. Lawrence River. The report recommended the development of a comprehensive program to locate sources of pollution; to bring these sources under control or to eliminate them; to develop and adopt uniform regulations at federal, state and provincial levels concerning discharge of wastes from pleasure craft and vessels; to encourage and support research and related activities; and to establish data centres on both sides of the border to facilitate the exchange of data. In December 1965, the International Joint Commission summarized the Boards' findings and issued its own "Interim Report" to the Governments of Canada and the United States.

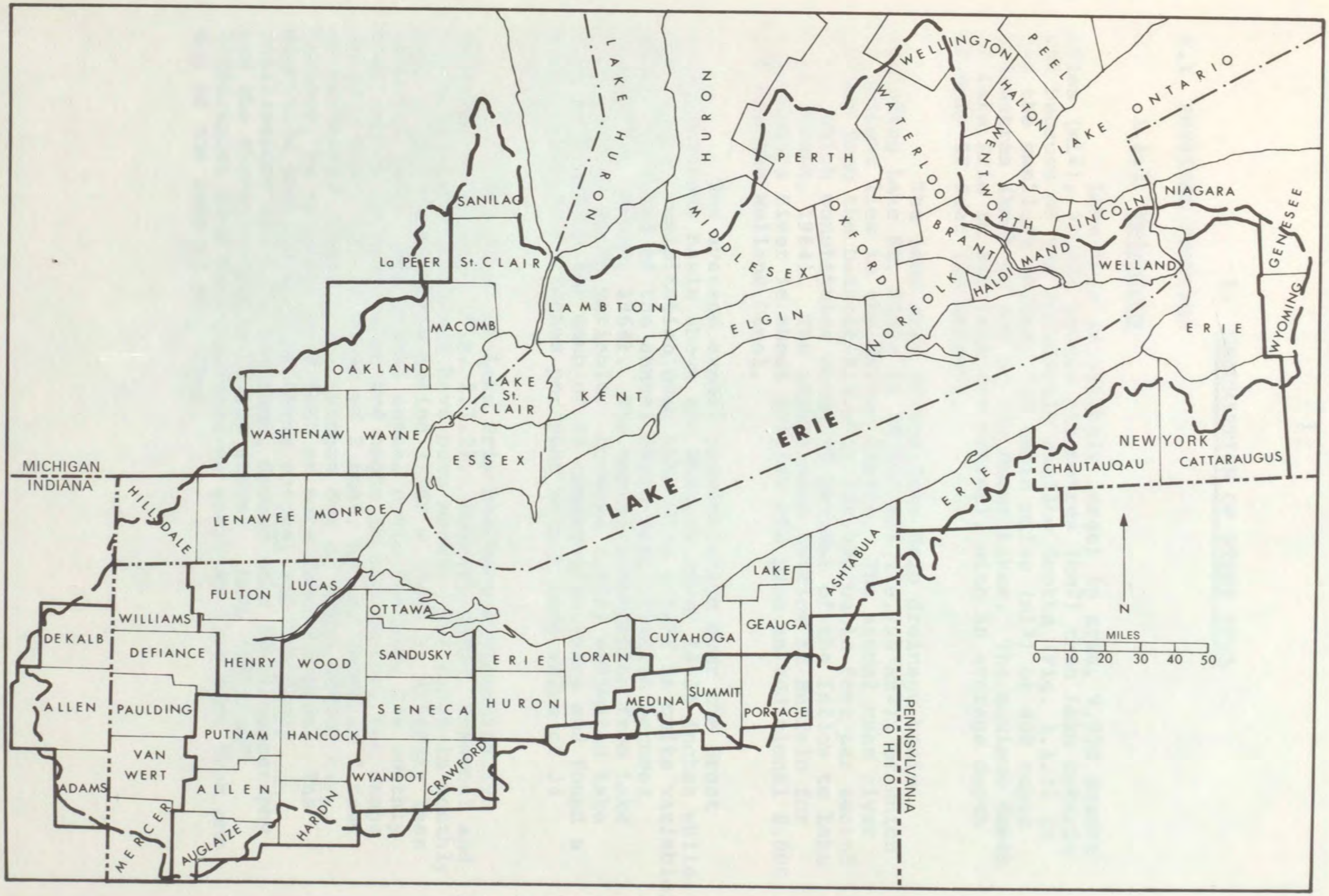
A second interim report was prepared by the Advisory Boards and submitted to the Commission in June, 1968. The report reiterated the conclusions stated in the 1965 report and noted the achievements in pollution abatement since that time. A number of other pollution reports commissioned by federal, state and provincial agencies participating in this study have been tabled with the Advisory Boards. These have been thoroughly reviewed and recognized in the planning of surveys, preparation of data or as source documents.

PRESENT REPORTS

This report has been prepared in three volumes. In Volume 1 the Boards have endeavoured to summarize the findings and to identify the critical problems of pollution, and pollution control measures which are of immediate concern to both countries as well as those long range problems which must be brought under continuing review and study. Volume 2 contains the scientific and engineering data and findings which have been used to determine the sources and levels of pollution in Lake Erie, as well as recommendations for the necessary remedial measures. Volume 3 contains similar information for Lake Ontario and the international section of the St. Lawrence River.



Geographical reference map for Lake Erie and Lake Ontario.



Counties of the Lake Erie drainage basin.

1. DESCRIPTION OF STUDY AREA

1.1 PHYSICAL FEATURES

1.1.1 Hydrology

Lake Erie is slightly larger in area, 9,970 square miles (mi^2), 25,821 square kilometres (km^2) than Lake Ontario and because of its relatively shallow depths (Fig. 1.1.1) it has the smallest volume, 110 cubic miles (mi^3) or 458 cubic kilometres (km^3) of any of the Great Lakes. The maximum depth of Lake Erie is 210 feet (64 metres), with an average depth of only 58 feet (18 metres).

The land area of the Lake Erie drainage basin including Lake St. Clair is 29,650 mi^2 (76,790 km^2), of which 70 percent lies in the United States. The annual mean river inflow from the Detroit River is 178,000 cubic feet per second (cfs) which constitutes about 90 percent of the inflow to Lake Erie (Brunk, 1964). The annual mean outflow at Buffalo for the Niagara River is about 194,000 cfs plus an additional 8,000 cfs via the Welland Canal.

The average annual precipitation over the Great Lakes drainage basin above the Niagara River is 31 inches while the annual precipitation over Lake Erie itself is quite variable. About one-third of the annual basin precipitation becomes streamflow (Brunk, 1964). The annual evaporation from Lake Erie is also quite variable. Derecki (1964) estimated Lake Erie evaporation for each of 23 consecutive years and found a range of 29 to 42 inches per year with a mean value of 34 inches.

The level of Lake Erie has been systematically measured since 1860 (Fig. 1.1.2). Hourly, daily, seasonal and longer period variations have been noted. The range in monthly mean values during this period (1860 - 1964) is slightly less than 5.5 feet. The normal annual cycle features low monthly mean levels in mid-winter and highs in mid-summer, the range usually being in the order of 2 feet, but as large as 3 feet on occasion. Local level changes due to storm action may, however, be as great as 6 feet or more from the mean. The magnitude and duration of these surges, and the decay oscillations which follow them, depend upon local topography and the characteristics of the storms. Lake "tilting" differences have been measured as great as 13.5 feet from one end of the lake to the other.

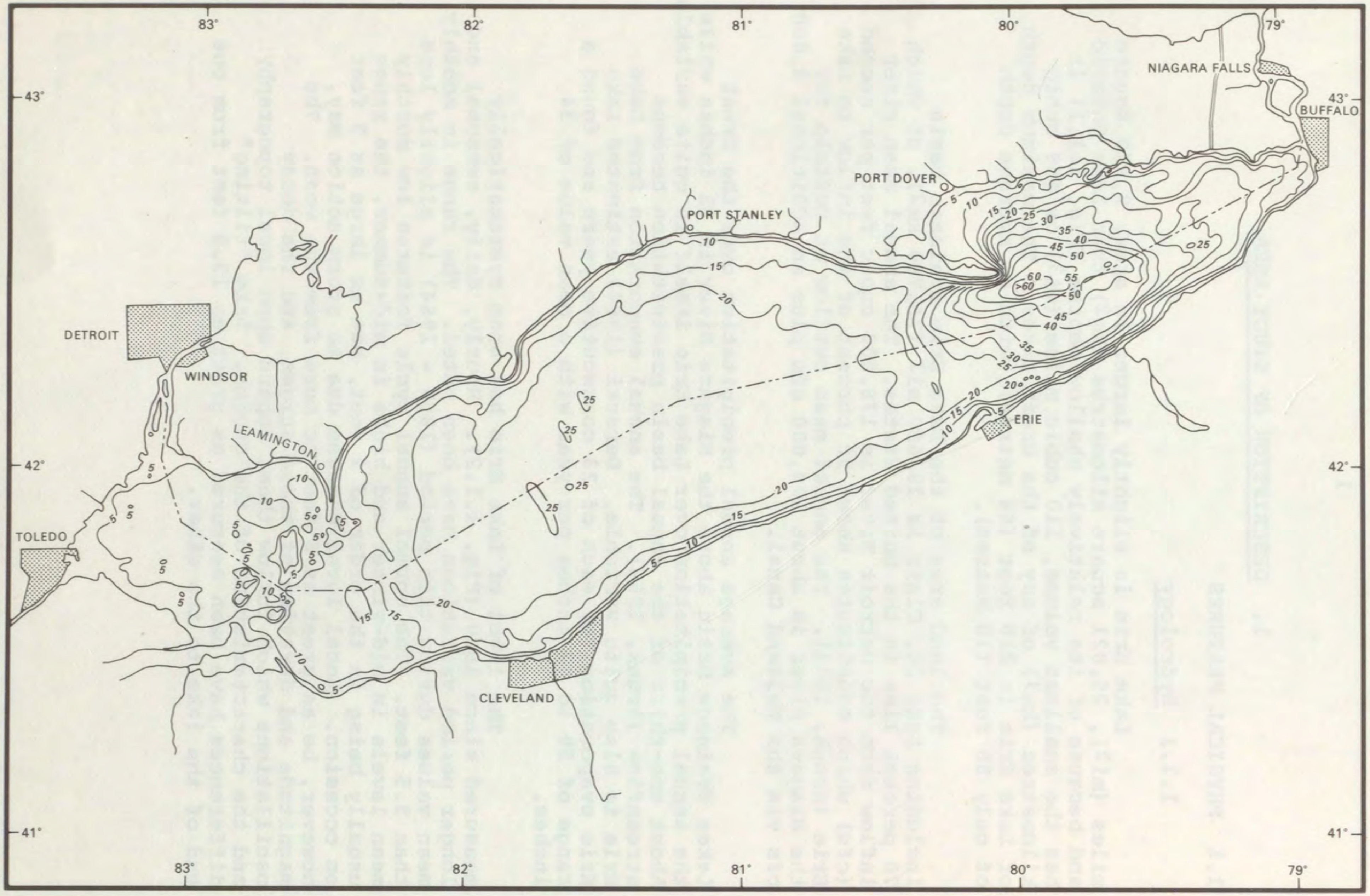


Fig. 1.1.1 Lake Erie bathymetry (metres).

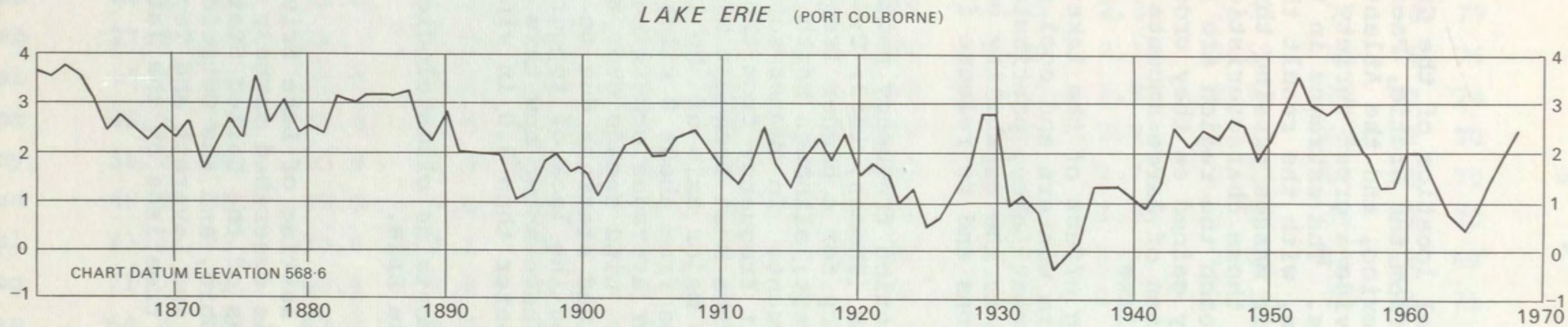


Fig. 1.1.2 Yearly mean water level variations (in feet) referred to the International Great Lakes Datum, 1955.

1.1.2 Climate

The continental location of the Great Lakes basin is such that air masses from the Arctic, Pacific Ocean, Western North America, Gulf of Mexico, and the Atlantic Ocean can converge upon it and provide a great variety and range of meteorological conditions. The extremes in these conditions are tempered by the lakes, with the result that the continental characteristics of the air masses passing through the region are modified somewhat to those characteristic of a marine climate. Storms which reach the region are frequently rejuvenated by the energy gained as they cross the lakes, often resulting in the deposition of large amounts of rain or snow on the lee sides of the lake.

The moderating effect of the lakes on air temperature results in relatively warm winters and cool summers in the shoreline areas of the Great Lakes, particularly along the lee shores. This is related to the capability of lakes to store heat in the heating seasons and to release it during cooling periods.

The wind direction frequency pattern for the Lake Erie region during winter (Thomas, 1953; U.S. Weather Bureau, 1959) indicates a tendency for a higher frequency of winds from the west and southwest; although north and northwest winds are also relatively frequent. In summer southeast winds alone are rare with the highest frequency from the northeast and southwest. In general, the most frequent wind directions are oriented parallel to the major axis of the lake. The average monthly wind speed varies from about 8 miles per hour (mph) to 18 mph with the higher averages occurring in winter at the eastern end of the lake. Wind speeds over the lakes differ from those of adjacent land stations due to the effects of atmospheric stability and the lack of topographic influences. Richards *et al.*, (1966) have shown how this results in lake/land wind velocity ratios greater than 3.0 in winter and less than 0.7 in summer.

Table 1.1.1 contains climatological data for selected land stations around Lake Erie.

1.1.3 Geology

The geologic setting of Lake Erie has been studied for over a century and is described largely in publications of the Geological Surveys of the United States, Canada, New York, Pennsylvania and Ohio, and the Ontario Department of Mines. Leverett (1902) and Leverett and Taylor (1915) prepared the first comprehensive treatises on the late glacial development

Table 1.1.1 Climatological data for three stations around Lake Erie.

T - Toledo (Toledo Express Airport) Ohio, Latitude 41°36'N, Longitude 82°48'W
C - Cleveland (Cleveland Hopkins Airport) Ohio, Latitude 41°23'N, Longitude 81°51'W
B - Buffalo (Airport) N.Y., Latitude 42°56'N, Longitude 78°44'W

	Air Temp. (°F)			Wind						Precip. (inches)			Rel. Humidity (percent)		
	T	C	B	mph T	dir T	mph C	dir C	mph B	dir B	T	C	B	T	C	B
Jan	26.4	28.5	25.5	12.6	WSW	12.5	S	17.4	WSW	2.25	2.38	2.78	77	78	77
Feb	27.3	28.6	24.7	12.5	SW	12.5	S	16.4	SW	1.86	2.12	2.59	75	76	76
Mar	35.8	36.8	33.0	13.0	SW	13.0	WNW	15.9	SW	2.86	2.89	2.72	72	73	74
Apr	46.5	47.3	43.8	12.8	WSW	12.0	S	14.8	SW	3.25	2.73	2.55	69	69	70
May	58.2	59.1	55.4	11.0	ENE	10.5	S	13.2	SW	2.95	2.73	2.47	68	69	70
Jun	68.6	69.4	65.5	9.8	SW	9.5	S	12.5	SW	3.55	3.05	2.70	69	69	70
Jul	73.1	73.7	70.6	9.1	SW	8.9	S	12.1	SW	2.65	3.04	2.43	68	68	69
Aug	71.0	71.9	68.9	8.8	SW	8.5	S	11.7	SW	2.69	2.64	2.54	70	70	71
Sep	64.2	65.5	62.4	9.7	SW	9.5	S	12.8	S	3.02	3.13	3.01	72	71	73
Oct	52.7	54.4	51.2	10.5	SW	10.2	S	14.1	S	2.32	2.42	2.49	72	71	74
Nov	39.8	41.7	39.9	12.4	SW	12.8	S	16.4	S	2.15	2.66	3.09	75	74	74
Dec	28.9	30.9	29.0	12.3	SW	12.9	S	17.0	WSW	2.29	2.29	2.92	78	76	76
yr	49.4	50.6	47.5	11.2	SW	11.1	S	14.5	SW	31.84	32.08	32.29	72	72	73
(a)	(b)	(b)	(b)	77	9	16	8	62	8	(b)	(b)	(b)	17	16	18

(a) years of record or (b) 1921-50 mean.

Climatology and weather services of the St. Lawrence Seaway and Great Lakes, U.S. Dept. of Commerce, Weather Bureau, Technical paper #35, pp. 61-65, 1959.

of Lake Erie. Summaries by Hough (1958, 1963) include both bedrock geology and geology of the unconsolidated deposits in the Lake Erie basin.

The basin of Lake Erie is an erosional feature entirely. Its location, orientation and shape are controlled to a large degree by the structure and lithology of the underlying bedrock.

Marine sedimentary rocks largely composed of limestone, dolomite, shale and sandstone strata dip gently towards two major basins of accumulation - westward to the Michigan basin centred in the lower peninsula of the State of Michigan and southward to the Appalachian geosyncline southeast of Lake Erie in Pennsylvania and New York. All outcropping bedrock in the basin dates from the Paleozoic era and ranges in age from Upper Silurian to Mississippian (410 million years to 310 million years). As shown in Fig. 1.1.3 rock strata under western Lake Erie occur on a northeast trending arch between the two structural provinces. In this area strikes tend to swing from north in the eastern part through west to southwest in the western part. Two island chains of western Lake Erie are based on erosion-resistant eastward-dipping dolomite formations. The remainder of Lake Erie's basin is a composite of two simple depressions located in outcrop zones of weak shale and siltstone bedrock. Depths to bedrock in the eastern basin reach 500 feet, whereas the central basin reaches depths of about 300 feet. Gentle northern slopes of the bedrock basin are presumably controlled by bedding planes in resistant Devonian limestone formations whereas the steep south shore slopes which rise towards shore in a series of jagged steps are believed to represent the eroded ends of overlying weak shale and siltstone strata. The bedrock basin is mantled with thick unconsolidated glacial and late glacial deposits particularly in the eastern and central basins.

Following the Paleozoic era, the seas withdrew and the Great Lakes area emerged as a continental land mass. Presumably, a well-developed drainage system was established with major river valleys located in outcrop zones of weak (shale) bedrock. Deep tributary valleys now buried under glacial deposits in western Lake Erie and at Cleveland suggest that a master valley once trended eastward down the main Erie basin.

During the last two million years there occurred at least four major periods of glaciation separated by warm interglacial periods. It is believed that glacial scour localized by pre-glacial river valleys produced the extensive Erie bedrock basin as we know it today.

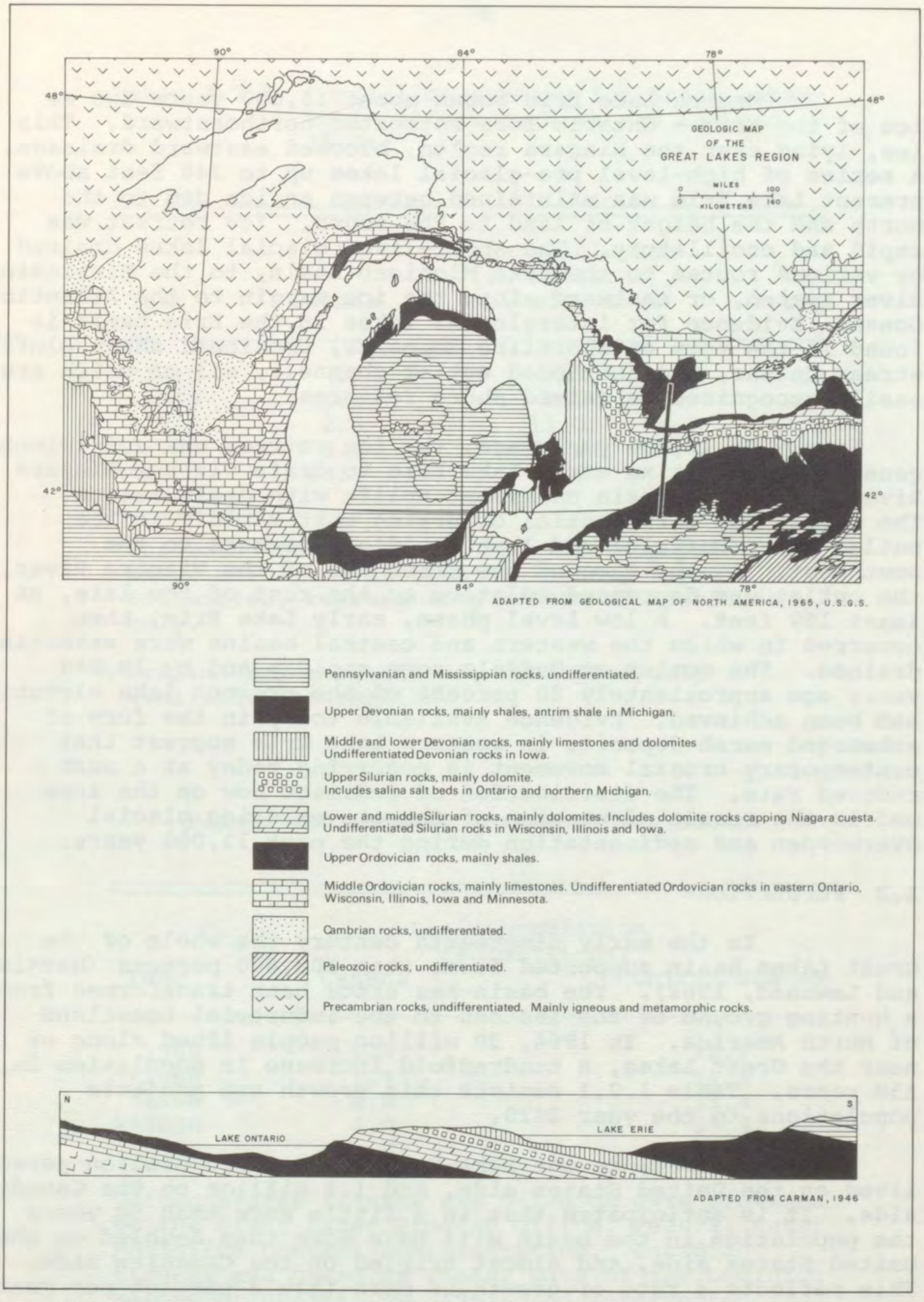


Fig. 1.1.3 Geologic map of the Great Lakes region and cross-section of Lake Erie and Lake Ontario.

Modern Lake Erie began about 15,000 years ago as ice of the Erie - Ontario lobe retreated northeastward. This ice, lying over the Niagara region, blocked eastward drainage. A series of high-level pre-glacial lakes up to 240 feet above present Lake Erie was maintained between an ice dam to the north and the height of land to the south. Ice retreat was rapid and oscillatory. The short-lived glacial lakes drained by various routes to the Lake Michigan basin, to the Mississippi River system, or eastward along the ice margin to the Atlantic Ocean. Evidence for interglacial lakes in the Erie basin is found in the form of shoreline deposits, erosional shore bluffs, stream deltas, and abandoned outlet channels, all of which are easily recognized as raised shore features.

By 12,000 years ago, the ice retreat was sufficiently general to permit an early Lake Erie to drain via the Niagara River. The Erie basin underwent uplift with deglaciation. The uplift was differential occurring most rapidly in the outlet area (Buffalo) and less rapidly elsewhere to the southwest. At the time of the first use of the Niagara River, the outlet was depressed relative to the rest of the lake, at least 100 feet. A low level phase, early Lake Erie, then occurred in which the western and central basins were essentially drained. The outlet at Buffalo rose rapidly and by 10,000 years ago approximately 80 percent of the present lake elevation had been achieved. Evidence available today in the form of submerged marsh deposits in western Lake Erie suggest that contemporary crustal movement is occurring today at a much reduced rate. The distribution of sediment now on the lake bed is the result of erosion of the pre-existing glacial overburden and sedimentation during the past 12,000 years.

1.2 POPULATION

In the early nineteenth century the whole of the Great Lakes basin supported fewer than 300,000 persons (MacNish and Lawhead, 1968). The basin has since been transformed from a hunting ground of the Indians to the industrial heartland of North America. In 1966, 30 million people lived along or near the Great Lakes, a hundredfold increase in population in 150 years. Table 1.2.1 depicts this growth and projects populations to the year 2020.

In 1966, in the Lake Erie basin, 10.4 million persons lived on the United States side, and 1.4 million on the Canadian side. It is anticipated that in a little more than 50 years the population in the basin will have more than doubled on the United States side, and almost tripled on the Canadian side. This reflects a rate of growth of more than 2 percent per year on the United States side, and greater than 4 percent on the Canadian side.

Table 1.2.1 Population summary for Great Lakes basin (After MacNish and Lawhead, 1968).

Year	Canada	Basin population (in millions) United States	Total
*1810	.1	.2	.3
1860	1.1	1.2	2.3
1910	2.5	11.3	13.8
1960	6.0	25.8	31.8
**2000	13.7	43.3	57.0

*Includes both immigrant and Indian populations; based mainly on statements in Encyclopedia Britannica, representing orders of magnitude only.

**Preliminary projections, from presently available information.

Population summary for Lake Erie basin.

Year	Basin population (in millions) Canada	United States
1960	1.2	10.2
1966	1.4	11.4
1986	2.0	15.4
**2020	4.0	23.5

United States figures are based on data provided by the Great Lakes Program Office, Federal Water Pollution Control Administration. Canadian figures are based on census data of the Dominion Bureau of Statistics (1961) and information provided by the Ontario Water Resources Commission from data and forecasts of the Ontario Department of Municipal Affairs, the Ontario Department of Economics and Development, and the Metropolitan Toronto Region Transportation Study.

A significant portion of the present population and future populations are expected to be confined largely to urban areas or settlements of 1,000 people or more. In 1960, 85 percent of the population in the United States portion of the Lake Erie basin was urban. By 2020, it is expected to be 94 percent urban. In Ontario the degree of urbanization is 77 percent. Stone (1967) using the 1961 Canadian census data has stated: "In Ontario 63 percent of the 1961 provincial urban population was contained in the 22 counties adjacent to Lakes Erie and Ontario, although only 39 percent of the rural non-farm and 40 percent of the rural farm populations were contained in these counties.". Also, the Economic Council of Canada (1967) lists the United States as sixth in terms of degree of urbanization of the most industrially advanced countries, and Canada eighth. It is interesting to note however, that Canada has had the fastest rate of urban growth among the industrially advanced countries during the post-war period (1951-61), with an average annual percentage growth of urban population of 4.1 percent, while the United States is second at 2.7 percent.

In the Great Lakes basin there are essentially four major zones of urbanization (Clark and Officer, 1962). These are: Toronto-Hamilton-Buffalo, Cleveland-Akron-Lorain, Windsor-Detroit-Flint, and Chicago-Milwaukee. Based on population projections, some planners have coined the term "megalopolis" to reflect the running together of vast urban areas. It has been suggested that such complexes are developing from Milwaukee, on the west shore of Lake Michigan, to Chicago and the Indiana-Michigan line; along the Detroit River; along the southern shore of Lake Erie; and the north and westerly shore of Lake Ontario. Beeton and Rosenberg (1968) have suggested that within the next 50 years a megalopolis extending from Milwaukee to Montreal will have a population of 50 million.

Such urban development, with the concomitant industrial expansion, will pose very great demands on the water resources of the Great Lakes.

1.3 LAND USE AND DEVELOPMENT

The Lake Erie drainage basin in Canada is composed of some 5,632,000 acres of land in Ontario. The United States portion is 13,343,000 acres distributed throughout five states; Michigan, Indiana, Ohio, Pennsylvania and New York.

1.3.1 Agricultural

Approximately 70 percent or 9,500,000 acres of the land in the United States portion of the Lake Erie drainage basin is devoted to agriculture. The total acreage can be broken down as follows:

	Canada	United States
Crop	1,574,000	7,421,000
Fallow & other	60,000	1,238,000
Pasture	340,000	797,000
Total	1,974,000 acres	9,456,000 acres

The types of farming are greatly diversified. The prevalent field crops in both countries are corn, hay, soybeans, wheat, and mixed grain. The major tobacco growing areas in Canada are in the Lake Erie basin. Beef, dairy, poultry and cash crop farming are practiced throughout the area. Truck crops and fruit growing are major activities in the United States. The realized gross income from agriculture in 1966 was estimated to be 262 million dollars in Canada and nearly 1 billion dollars in the United States.

1.3.2 Industrial

Although limited in extent at the present time, Canadian industry in the basin has been expanding steadily. A wide variety of products are manufactured in the basin. Products common to both countries include automobiles, machinery, fabricated metals, clothing, food products, chemicals and electrical equipment. On the United States side heavy chemical and steel industries predominate. The value added by manufacturing to the economy in the Canadian basin totalled approximately 925 million dollars in 1964; while that of the United States was 17 billion dollars. The industrial minerals industry is quite significant with natural occurrences of sand, gravel, clay, salt, shale, limestone and gypsum. Oil and gas exploration on the Canadian side has been extensive leading to a considerable number of producing gas wells. Exploration is being considered on the United States side.

1.3.3 Recreational

The total area devoted specifically to public recreational purposes within the watershed is 22,000 acres in Canada and 275,000 acres in the United States, or about 2 percent of the total basin area. Where sandy beaches exist warm water makes the shore of Lake Erie quite suitable for recreation. However, the majority of the shoreline is privately owned thus restricting its use for public recreation. The establishment of conservation areas is increasing and improving the recreational value of the inland waters considerably.

1.3.4 Municipal

In Canada the approximate total acreage occupied by the urban municipalities in the drainage basin is 76,000 acres for an urban population of 1.1 million persons. Urban area uses in the United States are about 1,200,000 acres for an urban population of 9.8 million.

1.3.5 Forestry

Reforestation, improved and unimproved woodlands occupy 221,000 acres of the Canadian drainage basin. The reforestation areas generally are managed in Ontario through agreements with the counties or townships. The forested areas in the United States are generally in the southeastern section of the basin and cover about 1,799,000 acres or 13 percent of the basin.

1.4 WATER USES

1.4.1 Public Water Supply[1]

At the present time the lands on the Canadian shoreline are generally rural in nature and direct usage from the lake is low. However, the limited ground water resources in the basin will force an increased use of lake water for all urban purposes in the future. In Ontario only 87,000 persons are served by public water supplies drawing about 20 million gallons per day (mgd) from Lake Erie. Approximately 59 percent of the total Canadian consumption is for industrial, commercial, institutional and irrigational purposes.

The United States communities on the lake shore withdraw 634 mgd through municipal facilities to serve 3.3 million people. About one-half of this supply is used for industrial purposes. This use will continue to expand as inland supplies are presently developed to near capacity.

Table 1.4.1 shows the population served and average consumption of the major public water supplies which utilize lake water. In addition, there are numerous privately-owned systems serving groups of cottages.

Municipal suppliers are equipped to provide chlorination and filtration with continuous coagulation depending upon the raw water quality. In addition, mechanical algae removal during peak growth seasons is practiced in the western end of the lake and to some extent in the eastern end. Carbon filtration for control of taste and odour also appears to be desirable during these periods.

[1]Water use data have been updated since the printing of Volume 1.

Table 1.4.1 Public water supply summary.

Area	Population served (thousands)	Average consumption mgd	*Treatment provided other than disinfection
Lake Erie			
Canada			
Bertie (Twp.)	18.0	1.70	Microstraining
Crystal Beach	2.0	.58	Filtration
Dunnville	5.5	10.20	Microstraining
Harrow	2.0	.27	Microstraining
Jarvis	.8	.08	Nil
Kingsville	3.5	.30	Conventional
Lake Erie Water Supply System St. Thomas-Taibotville		.66	Nil
Port Colbourne	17.8	2.9	Filtration, Taste & Odour Control
Port Dover	3.0	.71	Conventional
Port Rowan	1.0	.08	Conventional
Port Stanley	1.5	.20	Conventional
Raleigh (Twp.)	1.0	.12	Conventional
Union	27.0	4.07	Microstraining, Conventional
West Lorne	2.5	.33	Conventional
Wheatley	1.5	.31	Conventional
TOTAL CANADIAN	87.1	22.51	
United States			
Monroe, Michigan	23.0	4.0	Conventional, Taste & Odour Control
Toledo, Ohio	404.4	70.0	Conventional, Taste & Odour Control
Port Clinton	7.0	1.0	Conventional, Taste & Odour Control

Table 1.4.1 (cont'd)

Area	Population served (thousands)	Average consumption mgd	*Treatment provided other than disinfection
United States			
Sandusky	35.0	8.0	Conventional, Taste & Odour Control
Huron	5.5	1.0	Conventional, Taste & Odour Control
Vermilion	6.0	1.0	Conventional, Taste & Odour Control
Avon Lake	10.0	2.2	Conventional, Taste & Odour Control
Lorain-Elyria	123.0	19.0	Conventional, Taste & Odour Control
Cleveland	1,600.0	305.0	Conventional, Taste & Odour Control
Fairport-Painesville	26.5	5.0	Conventional, Taste & Odour Control
Madison on the Lake	13.6	0.7	Conventional, Taste & Odour Control
Mentor on the Lake	29.5	2.2	Conventional, Taste & Odour Control
Ashtabula	24.5	5.0	Conventional, Taste & Odour Control
Conneaut	17.0	2.0	Conventional, Taste & Odour Control
Erie, Pennsylvania	160.0	44.0	Conventional
Dunkirk-Fredonia, N.Y.	19.0	6.0	Conventional, Taste & Odour Control
Erie County	275.0	33.0	Conventional, Taste & Odour Control
Sturgeon Point			
Woodlawn			
Buffalo	535.0	125.0	Conventional, Taste & Odour Control
TOTAL U.S.	3,313.6	634.1	

*Conventional Treatment refers to: coagulation, sedimentation and filtration.

Area Designations
TWP - township

In general, Lake Erie is a satisfactory source of raw water for public supplies where complete treatment facilities are available. However, further degradation of lake quality would result in increased unit treatment costs.

1.4.2 Industrial Water Supply[1]

The average water consumption by the major industries obtaining water from the lake is shown in Table 1.4.2. The major industries utilizing process and cooling waters from Lake Erie are found in the United States and are largely base metal and metal reduction operations. These industries require vast quantities of cooling water and additional demands are expected in the future.

There are presently no public thermal generating stations located on the Ontario shore of Lake Erie. A large station is, however, under construction at Nanticoke, Ontario on the Lake Erie shoreline, with an immediate planned output of 1,000 megawatts (Mw) and an eventual output of 2,000 Mw. United States capacity in the basin is approximately 5,200 Mw in 11 plants. Considerable growth is anticipated. Two new plants are to be located in the United States section of the western basin, and are to be nuclear-fueled.

1.4.3 Transportation

Lake Erie is an important link in the Great Lakes commercial navigation system. The traffic is generally destined for ports in New York, Pennsylvania or Ohio or to the upper lakes. There are no major ports on the Canadian shore of Lake Erie. In 1966, there were 8,714 passages through the Welland Canal (St. Lawrence Seaway Authority, 1966) of both lake and ocean vessels. The inland trade cargo through the canal amounted to some 47 million tons of which 92 percent was in bulk form and the remainder general cargo. The most important commodities were iron ore, wheat and coal, but fuel oil, crushed stone, corn, barley, soyabeans and manufactured metal products were also handled. Bulk cargoes increased 12 percent in 1966 over the previous year. United States Lake Erie ports handled 124 million tons during 1966 much of which was interlake trade.

1.4.4 Agricultural Water Supply

Canadian use of Lake Erie for irrigation purposes is limited to two areas, Essex County in the Townships of Colchester South and Gosfield South, and near Port Burwell in the Townships of Bayham and Houghton. A number of small systems are scattered along the north shore.

[1] Water use data have been updated since the printing of Volume 1.

Table 1.4.2 Industrial water supply summary.

Area	Company	Average annual supply Process mgd	Average annual supply Cooling mgd
Lake Erie			
Canada			
Port Colborne	Algoma Steel Corp., Furnace Div.	3.0	13.0
Leamington	H.J. Heinz Co. of Canada Ltd.	0.5	3.5
Wheatley	Olmstead Fisheries 1961, Ltd.	0.4	1.2
TOTAL CANADIAN		3.9	17.7
United States			
Laguna Beach, Mich.	Enrico Fermi		190.0*
Erie, Mich.	Consumer Power		385.0
Monroe, Mich.	Ford Motor Co.		130.0
Toledo, Ohio	Toledo Edison		1,005.0
Port Clinton, Ohio	U.S. Gypsum	0.9	
Lorain, Ohio	Ohio Edison		121.0
Avon, Ohio	Cleveland Electric Illuminating		
Cleveland, Ohio	Cleveland Electric Illuminating		
Eastlake, Ohio	Cleveland Electric Illuminating		1,456.0
Ashtabula, Ohio	Cleveland Electric Illuminating		
Cleveland, Ohio	Cleveland Municipal Light		173.0
Fairport, Ohio	Diamond Shamrock	10.0	
Painesville, Ohio	Industrial Rayon Corp.	29.0	
Erie, Penn.	Hammermill Paper Co.	20.0	
	Pennsylvania Electric		144.0
	Erie Reduction	0.2	
Dunkirk, N.Y.	Niagara Mohawk		461.0
	Allegheny-Ludlum	1.5	
Westfield, N.Y.	Seneca Westfield Maid	0.5	
Buffalo, N.Y.	Hanna Furnace		26.0
	Buffalo River Cooling Water Project		100.0
Lackawanna, N.Y.	Bethlehem Steel	50.0	300.0
TOTAL U.S.		112.1	4,491

*Intermittent

The maximum withdrawal rate authorized by the Ontario Water Resources Commission, as of April 1968, was 11.4 mgd for 45 users. Tobacco and market garden crops accounted for 65 percent of the total quantity authorized. Other uses such as farm crops, fruit growing and general farm irrigation accounted for the remainder. There is little use of Lake Erie water for agriculture in the United States portion.

1.4.5 Recreation and Aesthetics

The primary value of the lake as a recreation area is its proximity to large urban centres such as Windsor, London, Detroit, Toledo, Akron, Cleveland, Erie, and Buffalo. The natural factors which increase the recreational value include the islands in the western end of the lake, the natural sand beaches and relatively warm water as compared to the other Great Lakes.

A total of 18,000 acres of parks and beaches is developed along the north shore of Lake Erie and 26,000 acres along the south shore. The location of the recreational areas is shown on Fig. 1.4.1 (Ontario Department of Tourism and Information, 1966, 1967; Ontario Department of Lands and Forests, 1967; United States Department of Interior, 1966). These areas are used by both the local population and vacationers from Canada and the United States.

Boating on the lake is extremely popular. Launching and docking facilities range from small tracts in municipal and provincial parks to marinas providing a full complement of services. Large marinas are located at Port Colborne, Port Dover, Port Stanley and Port Rowan and at all major cities on the southern shore. Numerous smaller facilities are available at the mouths of the tributary streams (Fig. 1.4.1).

1.4.6 Propagation of Aquatic Life and Wildlife

Commercial fishing continues to be of major economic importance in Lake Erie. The commercial catches in pounds per year are as follows:

Year	United States (pounds)	Canada (pounds)
1963	17,238,000	34,233,000
1964	13,354,000	25,381,000
1965	13,524,000	35,096,000
1966	12,697,700	41,424,000
1967	11,614,900	37,771,000
1968	11,920,700	39,416,000

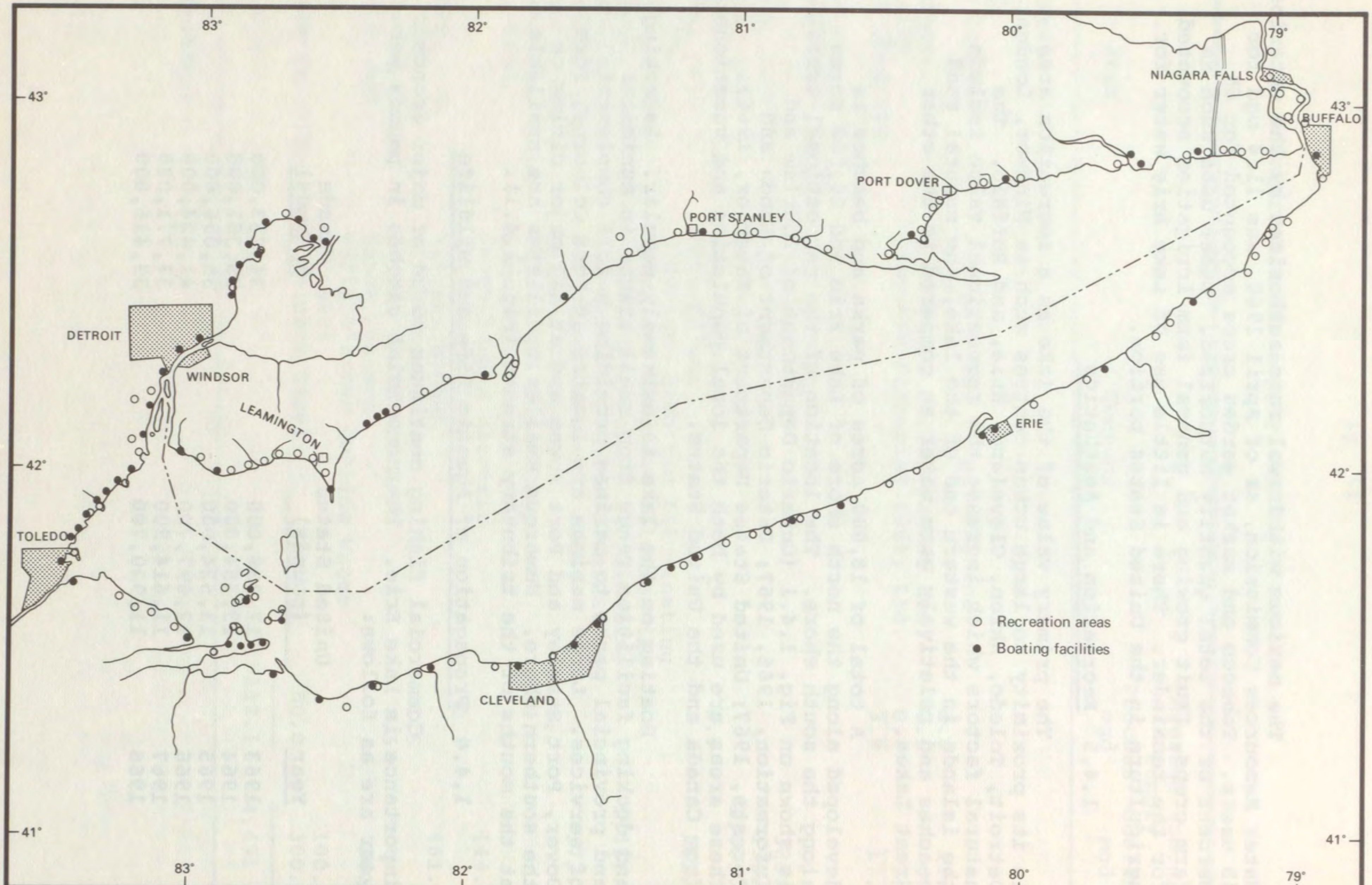


Fig. 1.4.1 Lake Erie recreation areas.

Some 20 commercially valuable species are caught. At present, perch and smelt account for the major poundage of the commercial catch. The total catch in 1966 had a market value of $4,280,000. Although the weight increased by 11 percent over the previous year, the value decreased by about 7 percent. This was attributed to a decrease in the market value of yellow perch during the first half of 1966. The value of the 1967 catch was estimated to be $4,666,000. The figures for the market value of the 1968 catch are not readily available.

Historically, the Lake Erie fishery has been affected by great changes which in some cases were almost disasters. There have been collapses in the production of a number of commercial species including the sauger, lake herring, whitefish and blue pike. Long term fishery statistics have been used to trace the abundance of fish stocks, production of fish and commercial activity. There has been a decrease in the catch of prime fish and an increase in those of lower commercial value.

Commercial fishing is concentrated in the western and central basins. In Canadian waters the area is confined to the northern part of the western basin and offshore from Pointe Pelee east to Port Maitland. Principal Ontario ports include Kingsville, Wheatley, Port Stanley and Port Dover. The Ohio ports of Sandusky, Huron, Vermilion, Lorain, Cleveland and Fairport land about 80 percent of the United States catch. Although trawling has recently been introduced, gill netting and trap fishing are still employed to a large extent.

Sport fishing is extensive in protected areas of the lake. Pike, maskinonge (muskellunge) and bass are caught near the mouth of the Detroit River. Bass, pike and some panfish are caught at Inner and Long Point Bays, Rondeau and in the western basin west of Point Pelee at Pigeon Bay and the islands. Offshore areas on the southern shore receive considerable fishing pressure. Three of the better areas are the western islands region, Sandusky Bay and Presque Isle State Park.

Water fowl in large numbers are found at Long Point and Pelee Point and at Kingsville which is the location of a bird sanctuary. Pelee Point, renowned as a haven for migrating birds, supports many unusual plants and animals absent elsewhere in Canada. The park includes extensive fresh water swamps and marshes. Migratory fowl utilize the southern shores of Lake Erie and the marsh areas in the western basin. Many birds winter near the Detroit River. Muskrat trapping is of some economic importance, but game species are relatively scarce except on privately owned hunting areas.

1.4.7 Waste Assimilation

Developments along the north shore are generally agricultural and recreational. Eight communities with a population greater than 500 persons including a hospital complex are situated near the shoreline. Five of these communities have municipal pollution control facilities treating a combined average sewage flow of 3.46 mgd. The other three communities without municipal treatment facilities have an estimated total waste flow of 0.35 mgd.

In view of the size of these communities the effects of the waste discharges are of local significance only. A similar situation applies to the present industrial development. The total average industrial waste water flow is about 21.6 mgd and the majority of this flow originates in the Port Colborne area. At the present time the major Canadian urban and industrial developments are inland and discharge their effluents to tributary streams.

The intense development along the southern shore has resulted in many direct waste discharges to the lake and to tributaries and as a consequence the quality of water has been reduced significantly. The direct industrial waste water flow is 6,603 mgd including the electric power industry. Twenty-one cities have direct discharges of 253 mgd from primary and secondary treatment plants to the lake and 11 more areas have inadequate septic tank systems.

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2. LAKE CHARACTERISTICS - PRESENT STATE AND TRENDS

2.1 PHYSICS

2.1.1 Thermal Regimes

As a consequence of the great range in the seasonal climatic conditions in the Great Lakes basin, each of the Great Lakes undergoes a cycle of heat storage and heat loss which involves exchanges of vast amounts of thermal energy. The resultant seasonal cycle of lake temperatures, at all depths, is of great importance to many physical, chemical and biological lake processes related to pollution. The significance of temperature effects on biological and chemical changes, such as the rates of exchange of oxygen across the air-lake interface and on the rates of biological productivity, are discussed in more detail in other sections of this report.

The report is based primarily on observations of water temperature taken from April to October, 1967, by the Department of Energy, Mines and Resources (EMR) and by the Department of Transport (DOT). This information was supplemented by airborne radiation thermometer surveys of surface temperatures (Richards, 1966). In general, the data collected in 1967 correspond to the characteristics of Lake Erie described by the Federal Water Pollution Control Administration (1968a) based on data primarily collected in 1965. An examination of wind and air temperature data from Windsor, Ontario, revealed that the summer of 1967 was slightly cooler (0.8°C) and slightly less windy (0.3 mph) than the long-term mean. The preceding winter was slightly warmer than the mean. It is impossible to relate this information quantitatively to the effects these slight deviations would have on the nature of the thermal regime in Lake Erie, but the broad features of the thermal conditions in 1967 should be reasonably typical.

A principal component of the heat budget of Lake Erie is incoming solar radiation. Table 2.1.1 contains values of solar radiation (Langleys per day) received at the surface of Lake Erie, which have been approximated from charts by Mateer (1955). Insolation is the major contributor to the energy budget (Bruce and Rodgers, 1962) and is a significant cause of variation of evaporation (Derecki, 1964).

Table 2.1.1 Mean daily totals of solar radiation (Langleys per day) (Mateer, 1955).

JAN.	110	JUL.	550
FEB.	190	AUG.	470
MAR.	290	SEP.	370
APR.	390	OCT.	240
MAY	450	NOV.	130
JUN.	550	DEC.	90

The Lake Erie water temperature, in the western basin, normally falls to 0.5°C about the middle of December, and remains at that level until the middle of March. Usually the western basin freezes over nearly completely. The surface water temperature in the remainder of Lake Erie drops to 0.5°C about the first of January, and remains at 0.5°C until the first of April. The central and eastern basins usually do not freeze over completely, but often are almost entirely covered by floe ice (Federal Water Pollution Control Administration, 1968a). Ice normally disappears in Lake Erie by the end of April. Just after the ice breakup in spring, the ice drifts eastward and accumulates in the eastern basin.

From the time of ice breakup, warming of surface waters and gradual mixing downward of heat takes place. Surface data from an airborne radiation thermometer survey in April (Fig. 2.1.1), reveal that the near surface temperature distribution of Lake Erie is more complex during the initial heating season in spring than it is in the summer and early fall (Fig. 2.1.2, 2.1.3). A comparison of average surface water temperature curves and air temperature curves (Fig. 2.1.4) shows that during the ice-free season there is a close relationship. The water temperature curve lags the air temperature by 9 to 12 days in spring and by 12 to 15 days in fall. The greatest departure is in mid-summer when the air temperature decline begins about three weeks before the water temperature decline (Federal Water Pollution Control Administration, 1968a).

The lake attains its highest overall temperature levels in August of each year (Fig. 2.1.2). The surface waters in the central and eastern basins are generally warmer for the southern half of the lake than for the northern side.

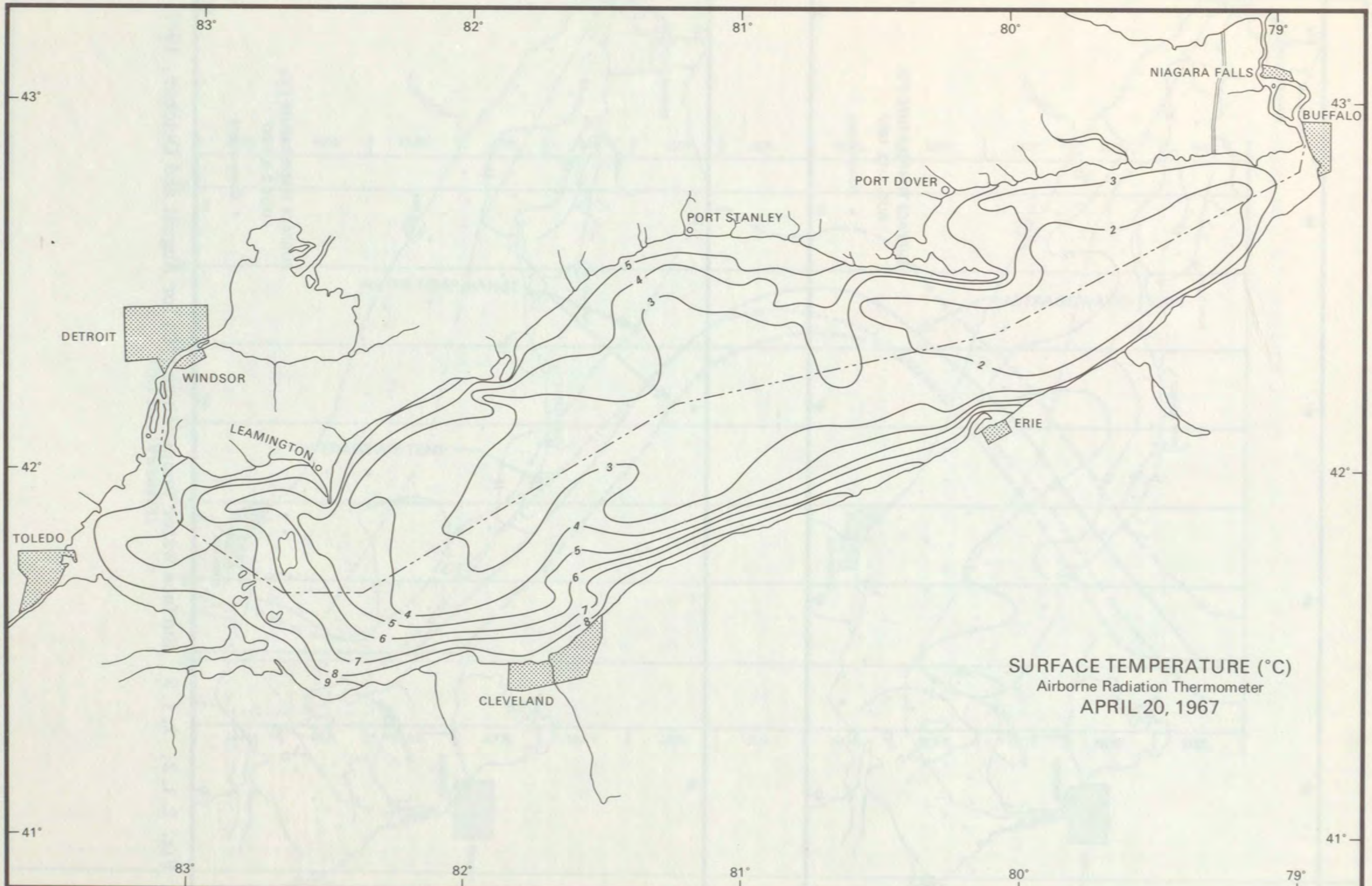
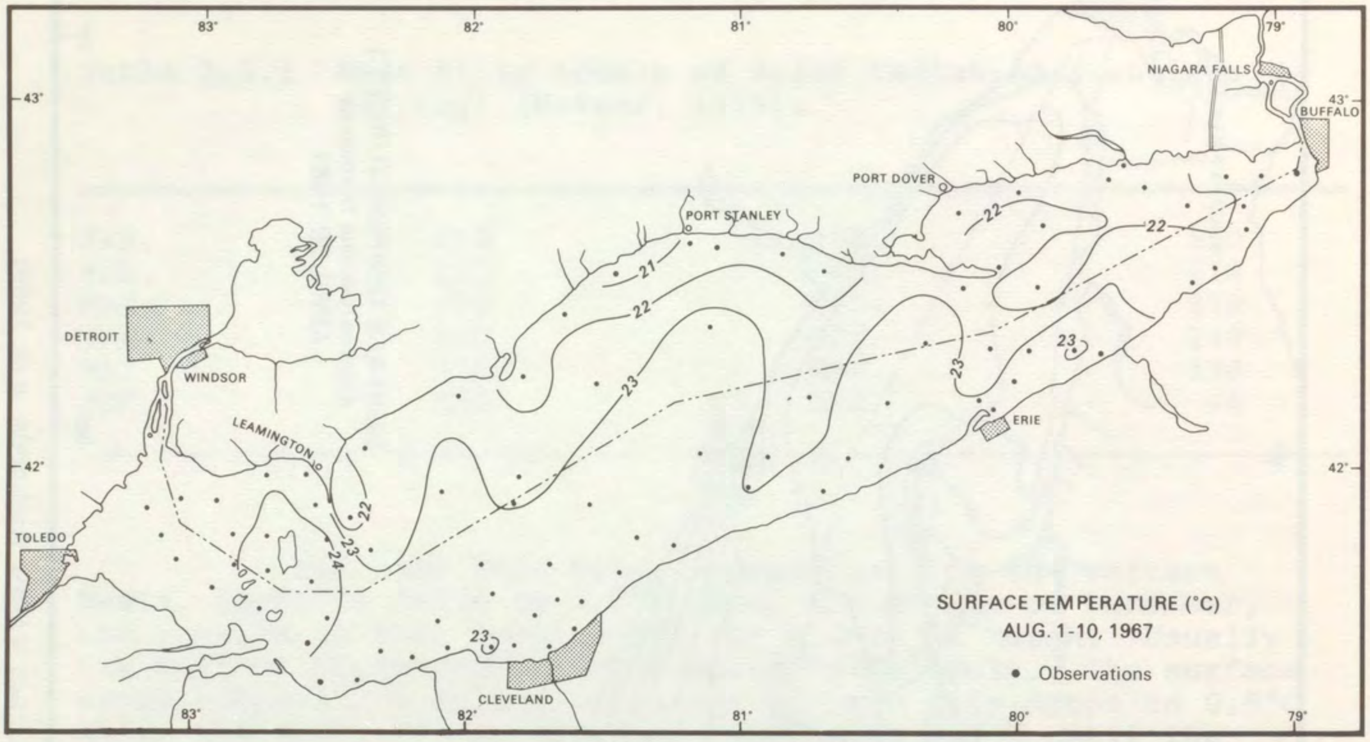


Fig. 2.1.1 Surface water temperature (°C) for April 20, 1967 (After Richards *et al.*, 1969).



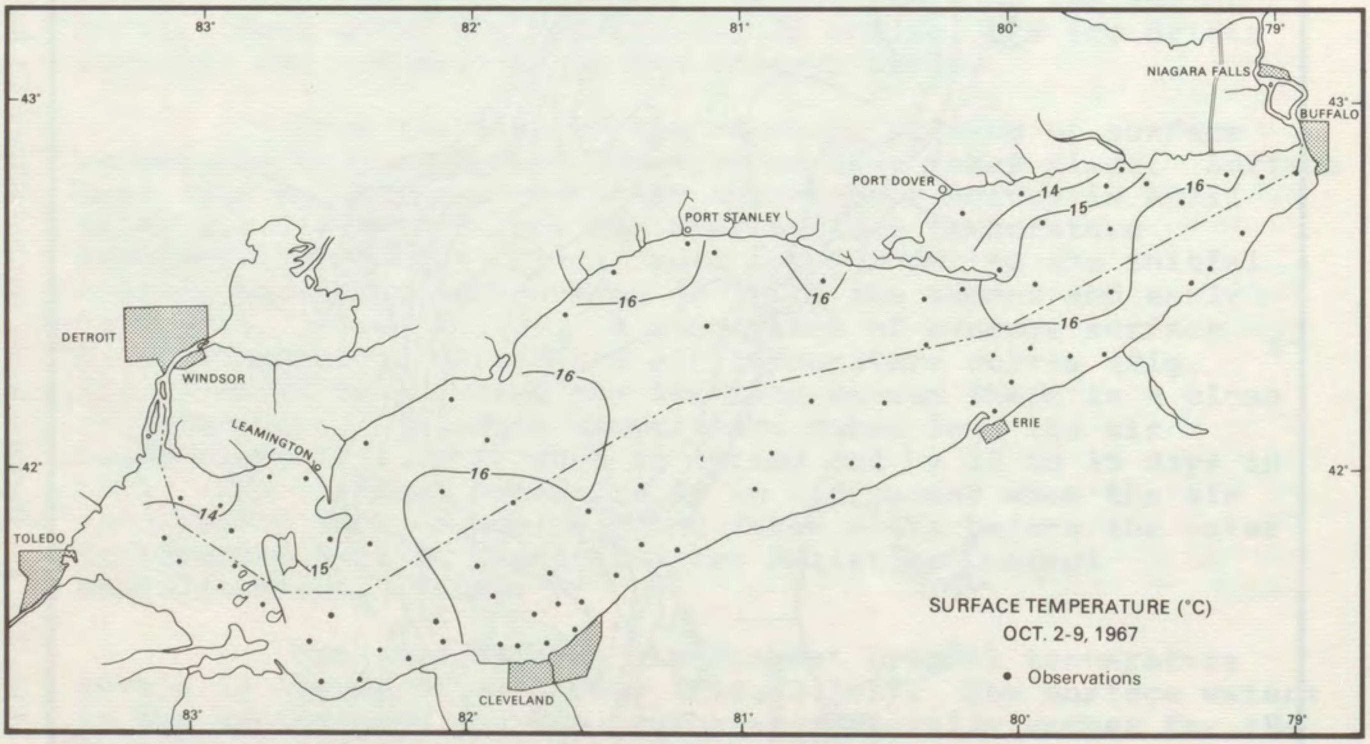


Fig. 2.1.2, 2.1.3 Surface water temperature (°C) for August and October, 1967.

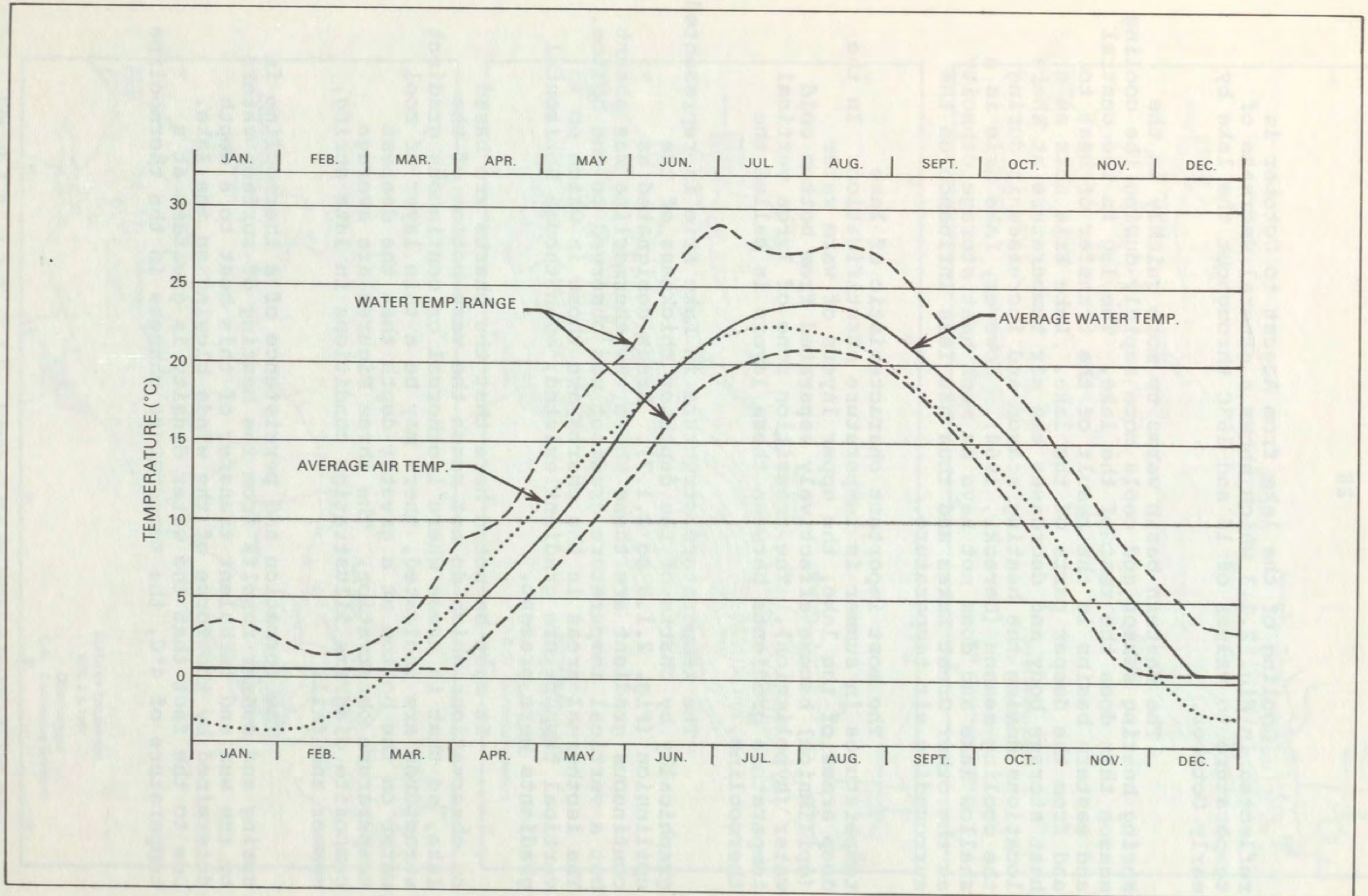


Fig. 2.1.4 Long term averages of water temperatures at Put-In-Bay, Ohio, and air temperatures at Toledo, Ohio (1919 - 1965).

Cooling of the lake from August to October is reflected in Fig. 2.1.3 which shows a general decrease of temperature to values of 14 and 16°C throughout the lake by early October.

The western basin warms up more quickly in the spring heating season and cools more rapidly during the cooling season than does the rest of the lake. The lag in the central and eastern basins is the result of the transfer of heat to and from the deeper parts of the lake. Lake Erie acts as a heat storage body and decreases the air temperature at shore locations during the heating season and increases it during the cooling season (Derecki, 1964). However, Lake Erie is a shallow lake and does not have as much heat storage capacity as the other Great Lakes and thus has less influence on the surrounding air temperature.

The most important characteristic of lake temperatures in summer is temperature stratification. In the deep areas of the lake, the upper layers of warm water (epilimnion) become effectively separated from bottom cold water (hypolimnion). The transition zone of large vertical temperature gradients between these layers is called the thermocline.

The temperature structure in Lake Erie is represented graphically by charts of the depth or thickness of the epilimnion (Fig. 2.1.5 to 2.1.7). Areas designated as continuous gradient are those where the thermocline was absent but a vertical temperature gradient was observed to the bottom. The isothermal areas in the charts are those in which no vertical temperature gradient existed, even though horizontal gradients were present.

It must be noted here that the charts are based on observations which do not reach the very bottom of the lake, so that in areas where isothermal or continuous gradient structures are indicated, there may be a thin layer of cool water on the bottom at a greater depth than the deepest temperature observation. The three Figures are average composite diagrams illustrating conditions in late spring, summer and fall.

The formation and persistence of a thermocline in spring and summer results from the heating of surface waters by the sun and turbulent transfer of this heat to a depth determined by the force of the winds blowing on the lake. Due to the fact that the water density is greatest at a temperature of 4°C, the temperature changes in the thermocline

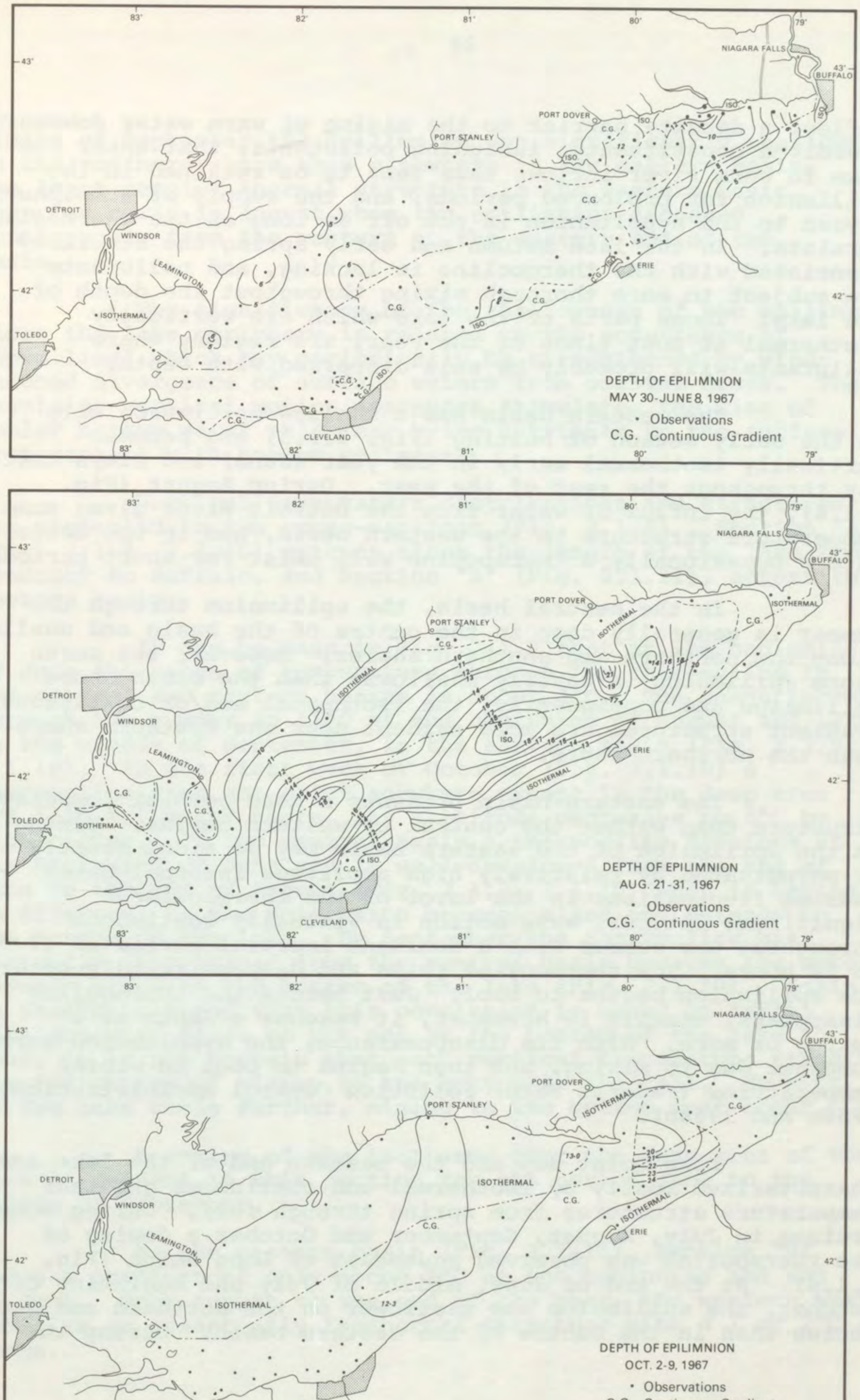


Fig. 2.1.5, 2.1.6, 2.1.7 Depth of the epilimnion (metres) for June, August and October, respectively, 1967.

reflect a density barrier to the mixing of warm water downwards. Dissolved constituents, including pollutants, that enter the lake in warm river inflows thus tend to be retained in the epilimnion for prolonged periods, and the supply of atmospheric oxygen to the hypolimnion is cut off as long as the thermocline persists. In the late autumn and early spring the stability associated with the thermocline is lacking, and pollutants are subject to more thorough mixing throughout the depth of the lake. Those parts of the lake which are vertically isothermal at most times of the year, are regions where pollutants will probably be well-dispersed with depth.

The western basin has a shallow epilimnion only in the early season of heating (Fig. 2.1.5) and becomes vertically isothermal early in the year (June) and stays that way throughout the rest of the year. During August (Fig. 2.1.6), the influx of water from the Detroit River gives some temperature structure to the western basin, and in the deeper waters occasionally a thermocline will exist for short periods.

In the central basin, the epilimnion through the summer is generally deep in the centre of the basin and shallow along the northern and southern shores. However, the north shore epilimnion is usually shallower than the south shore epilimnion and consequently, the isothermal and/or continuous gradient structures are more evident near the southern shore than the northern shore.

The eastern basin presents a more complex temperature structure than either the central or western basins. Mixing in the epilimnion of the eastern basin may be aided greatly or perpetuated by relatively high amplitude internal waves causing fluctuations in the level of the thermocline. Significant internal wave motion is virtually continuous throughout the summer with a dominant inertial period of 17 to 18 hours. The thermocline thins and deepens rapidly after the epilimnion begins to cool. Just before the thermocline disappears, usually in November, it reaches a depth of 30 metres or more. With its disappearance, the hypolimnion warms somewhat due to mixing, and then begins to cool to winter temperatures (Federal Water Pollution Control Administration, 1968a and 1968b).

Long Point Bay and the eastern end of the lake are characterized mostly by isothermal and continuous gradient temperature structures from spring through fall. During some cruises in July, August, September and October a doming of the thermocline was observed southeast of Long Point (Fig. 2.1.6). At the end of June, middle of July and beginning of October, the epilimnion was shallower on the northern and southern shores than in the centre of the eastern basin. During the middle of September the epilimnion was significantly shallower on the southern shore than elsewhere in the eastern basin. The least complex thermal structure in the eastern basin occurred early in August when the epilimnion deepened continuously from the western to the eastern end of the basin.

The significance of the shallowness of the epilimnion along the lake periphery is related to the occurrence of "upwelling" which may periodically be strengthened by wind-induced divergence of surface waters from coastal areas. The resulting vertical motion nearshore stimulates the rise of cooler bottom water which may bring nutrients to the surface from contact with bottom sediments.

Vertical temperature distributions and structures are presented in two cross-sections (Fig. 2.1.8). Section "A" (Fig. 2.1.9, 2.1.10) extends along the length of the lake from Sandusky to Buffalo, and Section "B" (Fig. 2.1.11), across the western basin.

It can be seen in Fig. 2.1.9 that at the beginning of June the range of temperature through the thermocline in the central and eastern basins is about 4°C. The range increases through the summer to 11°C at the beginning of August and 12°C in the middle of September, in the eastern basin (Fig. 2.1.9, 2.1.10). In the first week of October (Fig. 2.1.10) a thermocline does not exist anywhere except in the deep area off Long Point and there, its magnitude decreases to 5°C by mid-October. In the central basin a thermocline develops at the beginning of June and is well-developed from the end of June to the end of August (Fig. 2.1.9, 2.1.10) when it begins to disappear as the epilimnion becomes mixed and extends to the bottom of the lake. By September the thermocline has virtually disappeared from the central basin because the water becomes mixed to the bottom of the lake (Fig. 2.1.10). Again, it should be noted that this conclusion is based on serial data observed close to but not at the bottom of the lake. Thus, it is not certain that such vertical temperature structures are indicative of mixing to the bottom in the fall. However, as the lake cools further, mixing to the bottom must occur.

A doming of the isotherms over the deep area of the lake is evident in this section for the period June to the middle of September.

In the western basin (Fig. 2.1.11), Section "B" shows a gradient of only about 2°C at the beginning and end of June. From August to the end of the year, the western basin exhibits an essentially isothermal structure with a 1 or 2°C range.

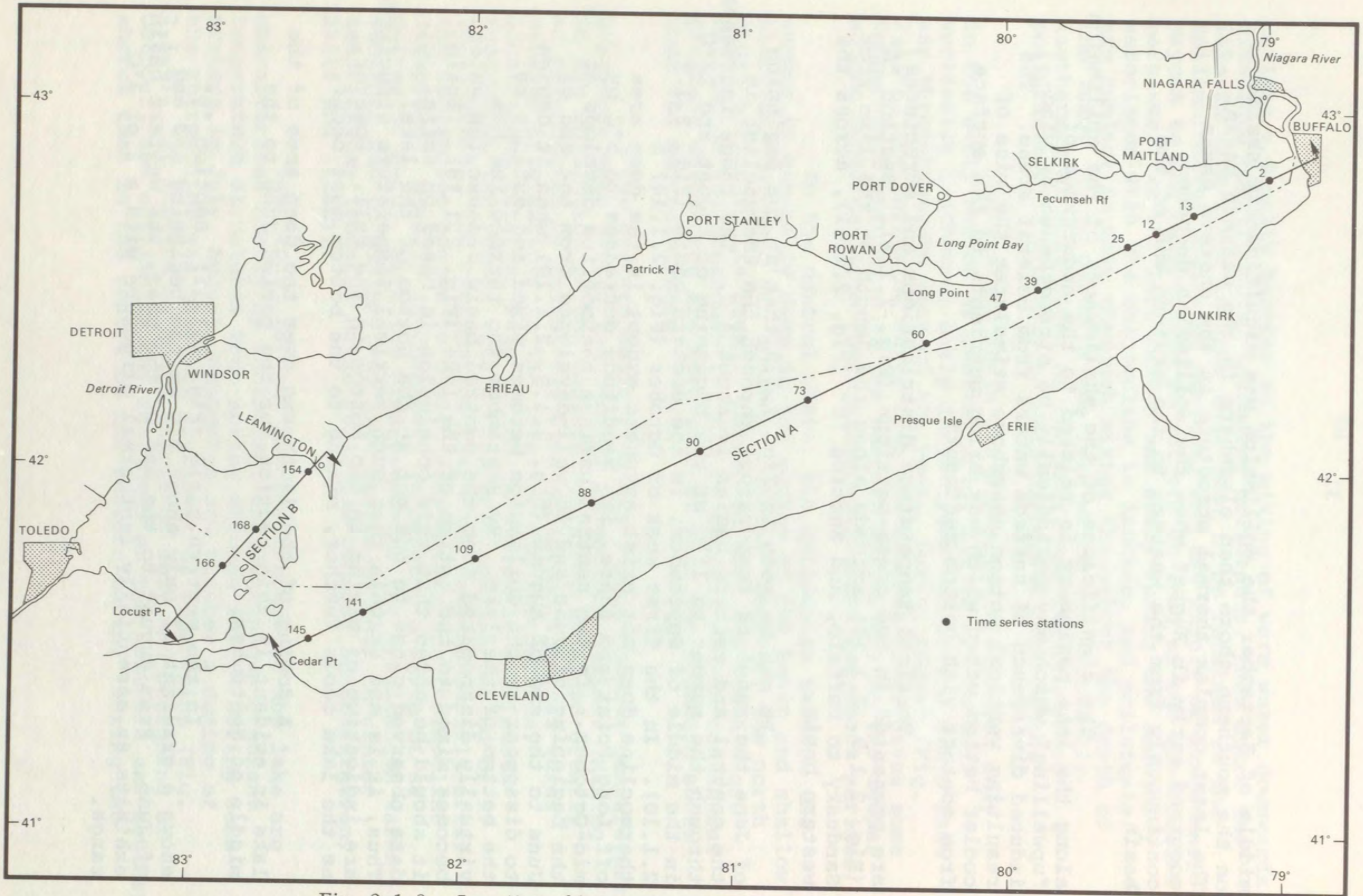


Fig. 2. 1. 8 Location of key sections and time series stations, 1967.

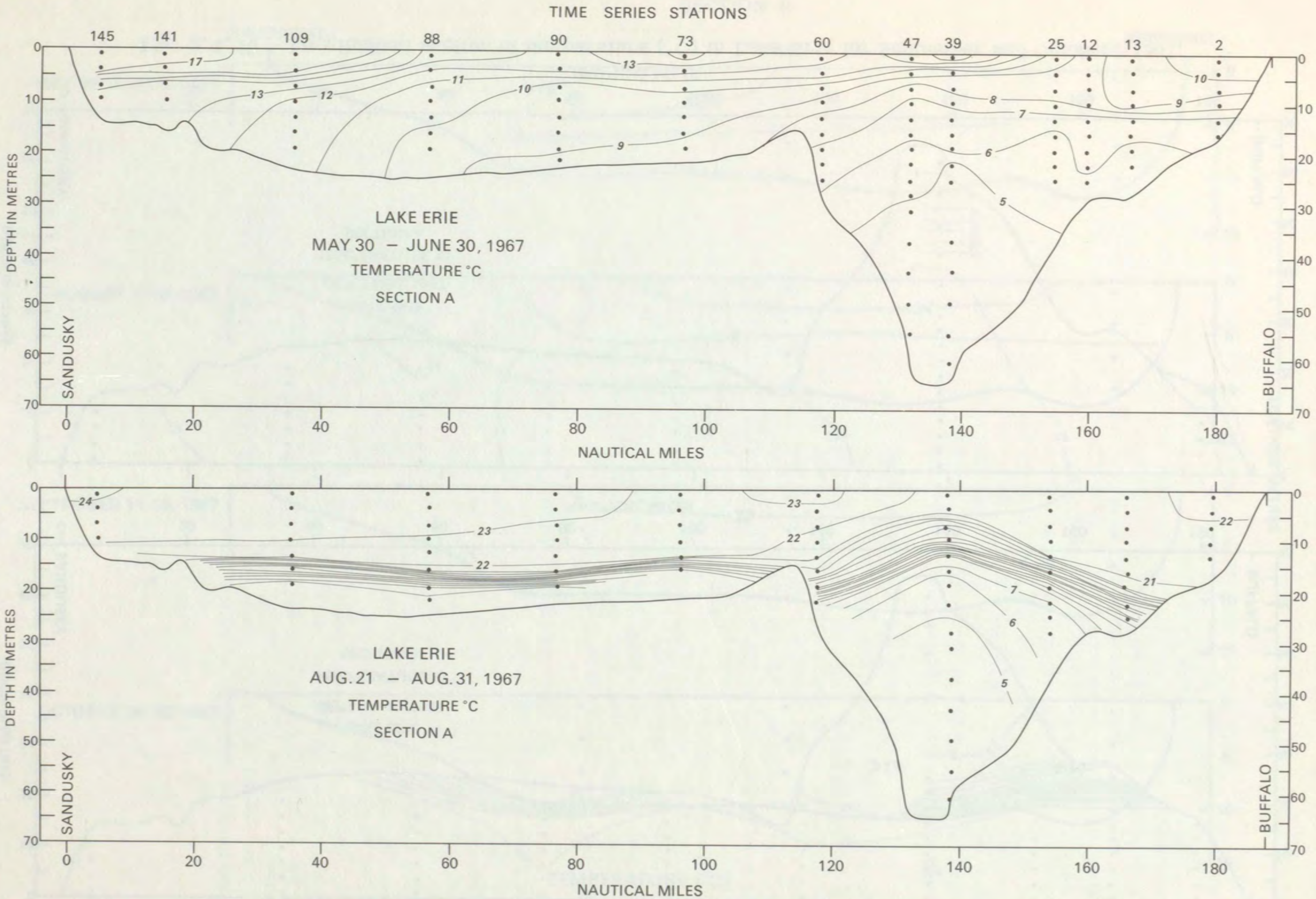


Fig. 2.1.9 Longitudinal section of temperature (°C) in Lake Erie for June and August, 1967.

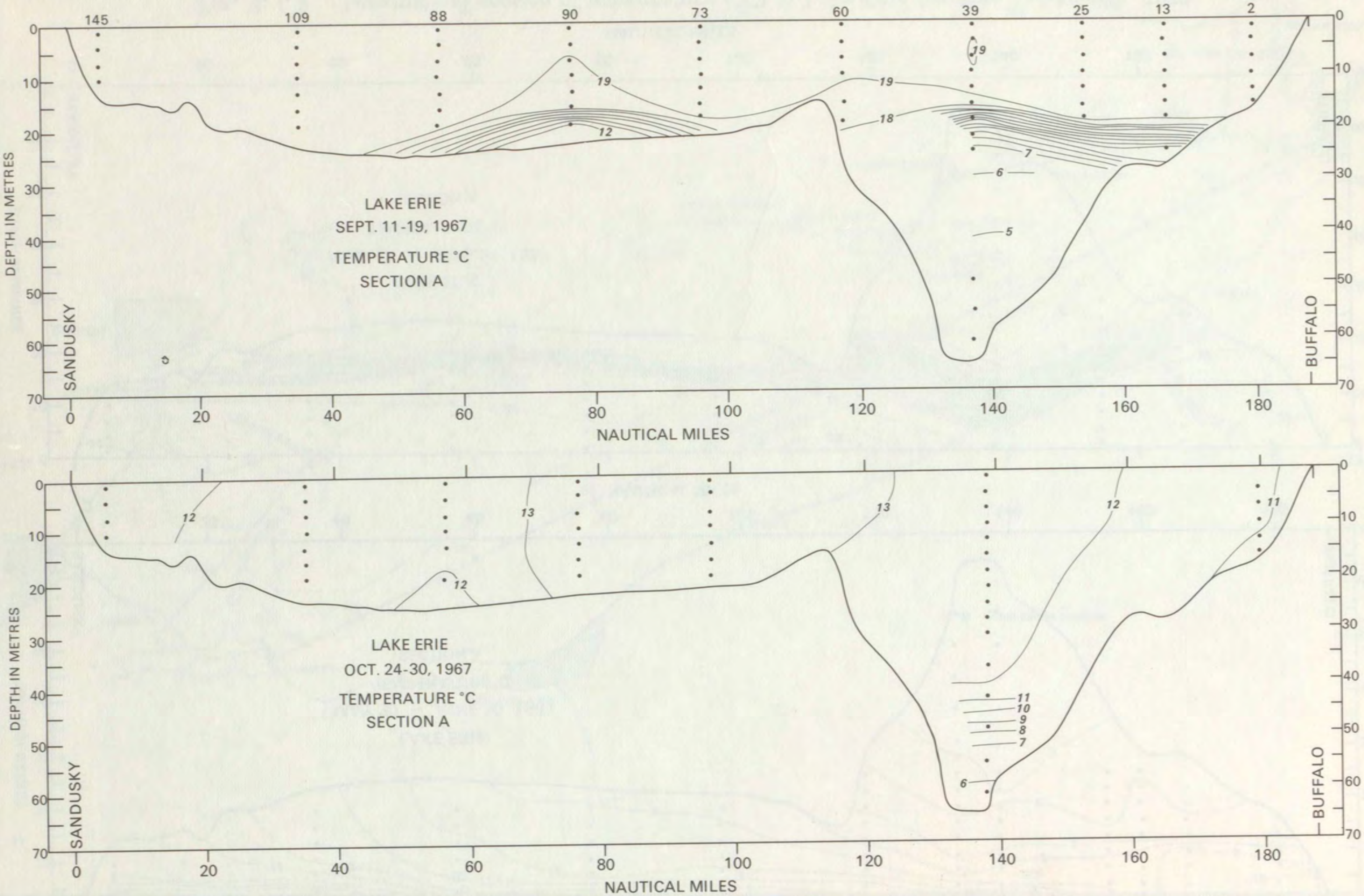


Fig. 2.1.10 Longitudinal section of temperature (°C) in Lake Erie for September and October, 1967.

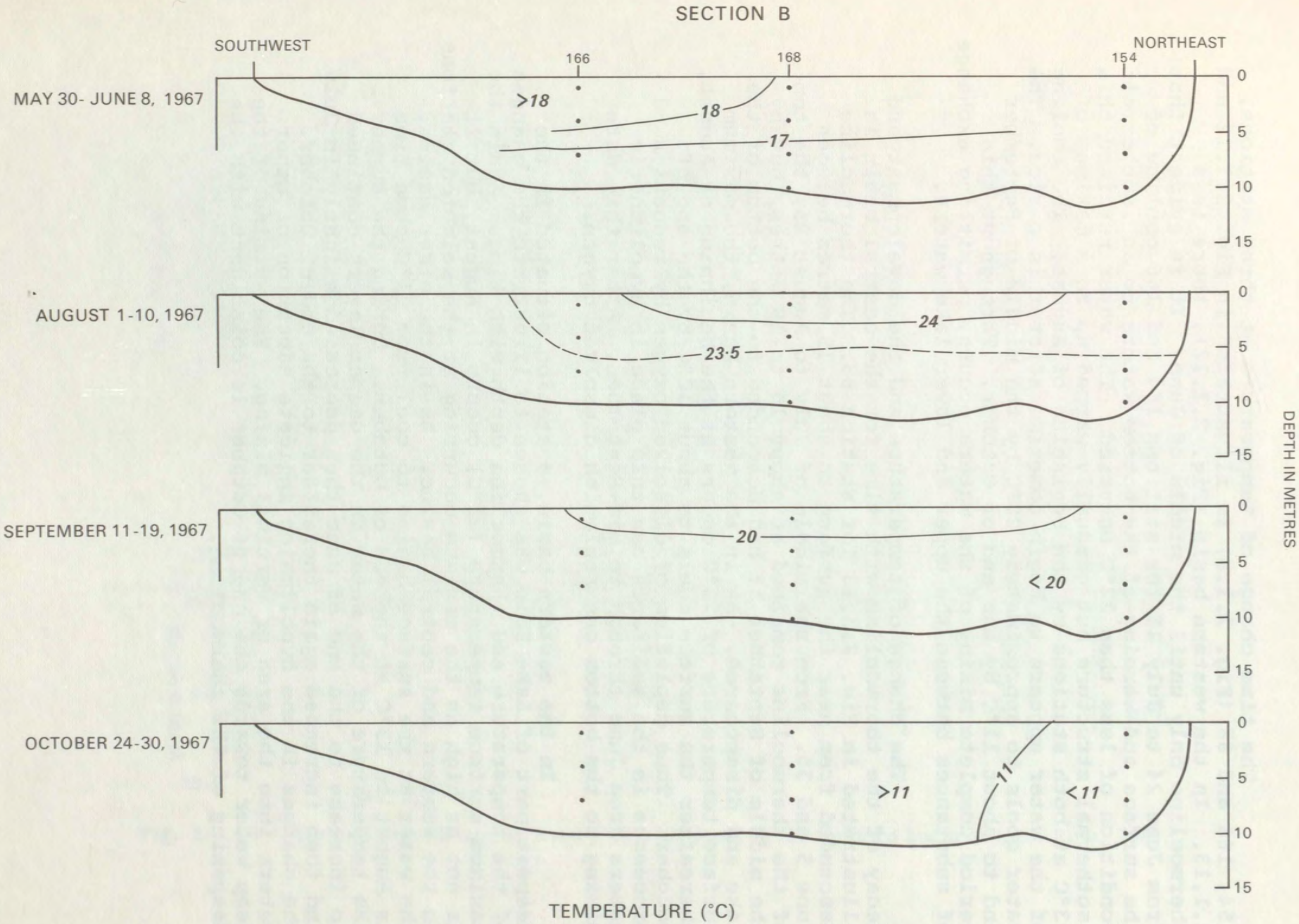


Fig. 2.1.11 Cross-section of temperature (°C) in the western basin of Lake Erie for June, August, September and October, 1967.

The time change of temperature at three stations, 154, 166 and 88 (Fig. 2.1.8) is illustrated in Fig. 2.1.12 and 2.1.13. In the western basin (Fig. 2.1.12), there is a thermocline only until the middle of June. It is evident that from June 24 to July 15 for stations 154 and 166 cooling of the surface and warming of the bottom waters to an isothermal condition of less than 22°C occurred. The water retained this isothermal structure but gradually warmed up to a maximum of 23°C at both stations by the beginning of August. The cooling of the water appears to begin sometime after this period. The water cools to approximately 20°C by the middle of September and to about 11°C by the end of October. Throughout this period complete mixing of the waters occurs, permitting exchange of substances between the upper and lower lake waters.

The change of temperature and the development and decay of the thermocline with time for the central basin is illustrated in Fig. 2.1.13 for station 88. The thermocline descended from near the surface to about 15 metres between June 5 and 30. From the middle of July to August 25, the top of the thermocline remained at about 16 to 18 metres, but by the middle of September it had descended to the bottom of the lake and disappeared. As in the western basin, the maximum surface temperature of 23°C occurs at the beginning of August, thereafter the surface cools to about 12°C by the end of October. Thus depletion of dissolved oxygen by reduction processes in the sediments can take place in hypolimnetic waters from June through to mid-September. After this date mixing to the bottom can replenish dissolved oxygen.

In the eastern basin, a station situated in the deepest part of Lake Erie was chosen to illustrate the changes of the temperature and thermocline depth with time. Again the maximum surface temperature (21°C) occurs in August, but it is not as high as the maximum occurring at the selected stations in the western and central basins. As in the other basins, the water at the surface begins to cool from 21°C some time in August to 13°C at the end of October. During the summer the temperature of the water in the deeper layers continued to increase to the end of June then decreased slightly in July and then increased again thereafter to the end of October. The changes in the hypolimnion indicate advection of other waters into the area or vertical mixing. The warming of the deep water towards the end of October is coincident with the deepening of the thermocline.

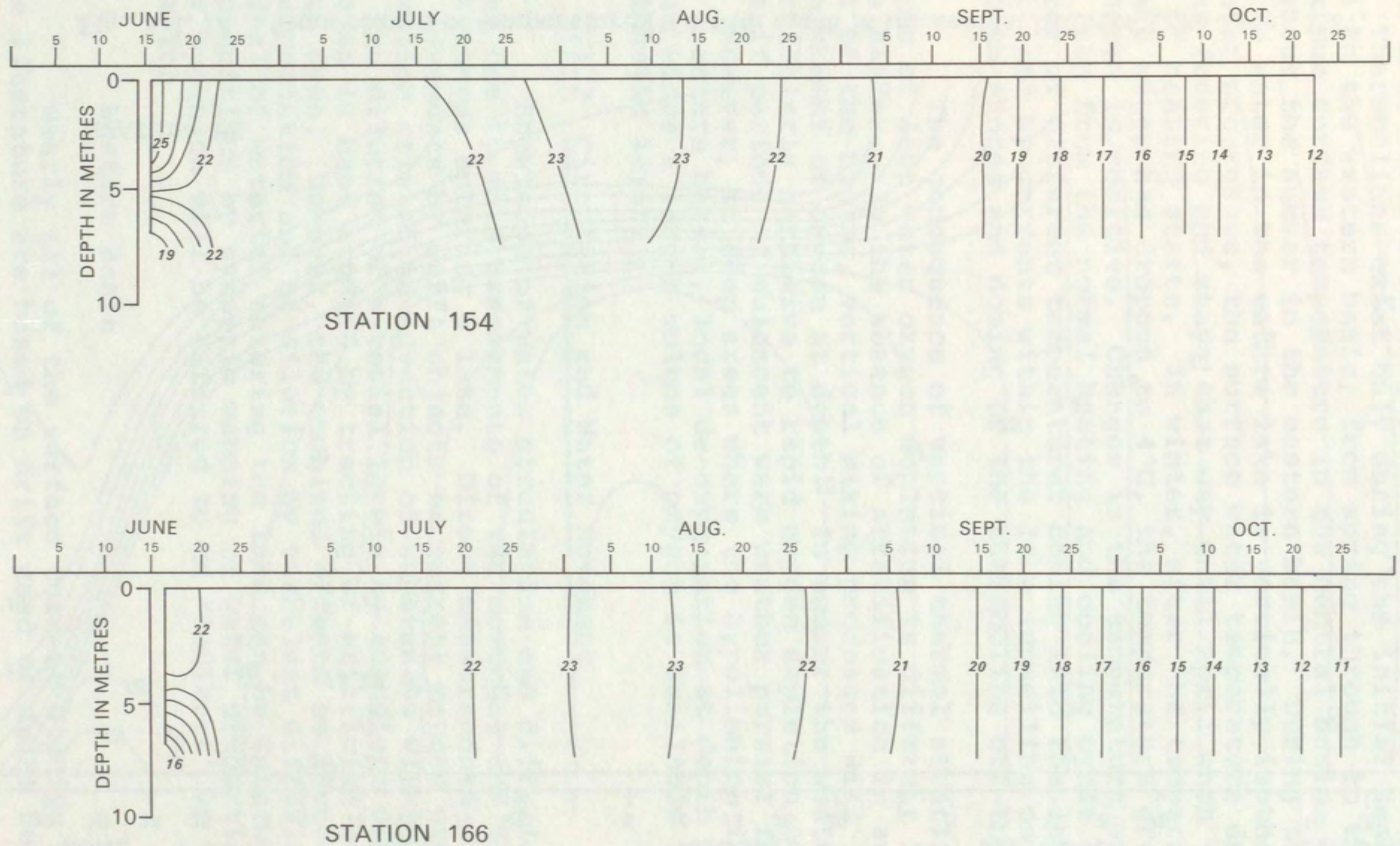


Fig. 2.1.12 Time change of temperature (°C) with depth in the western basin of Lake Erie, 1967.

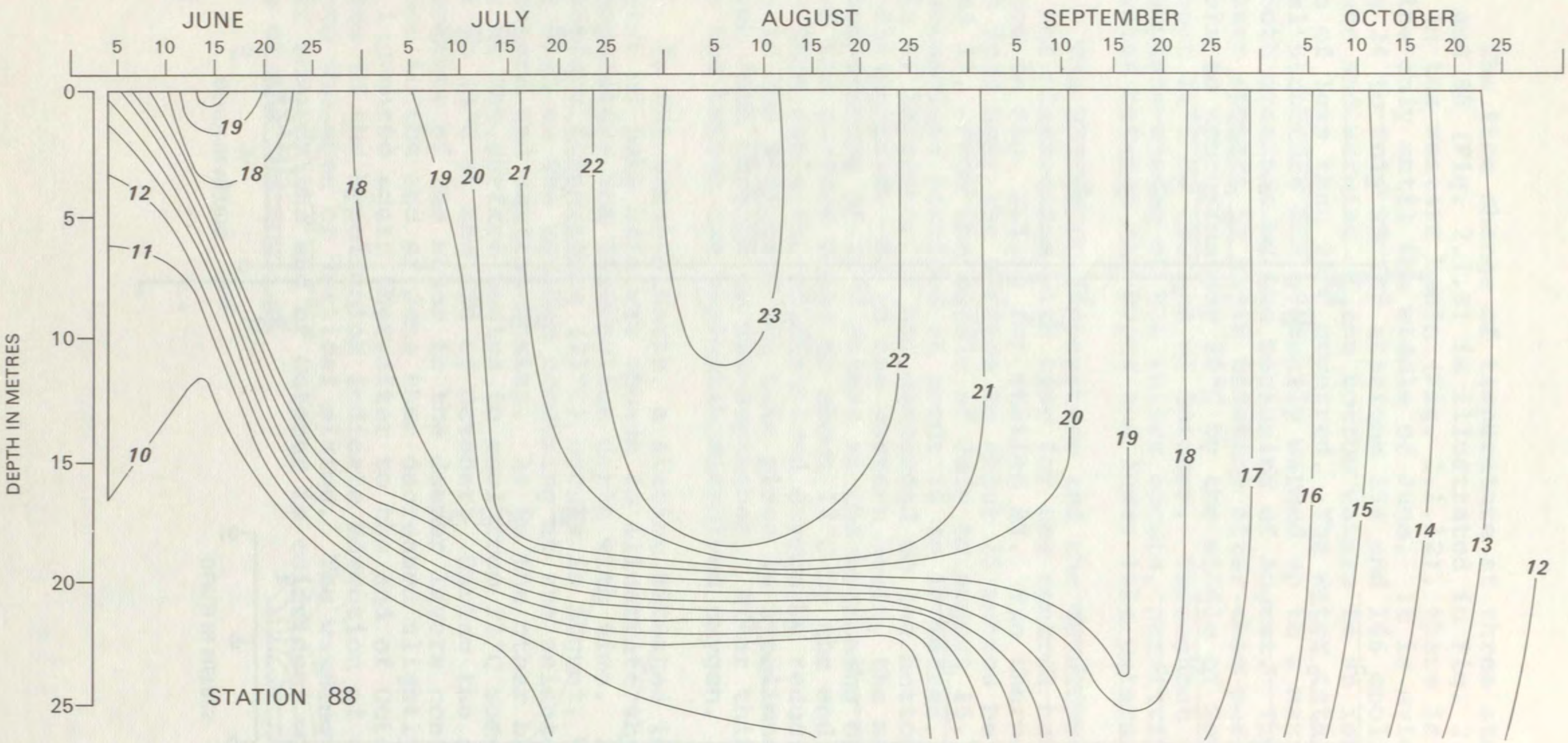


Fig. 2.1.13 Time change of temperature (°C) with depth in the central basin of Lake Erie, 1967.

In summary, it can be said that the shallow depth of Lake Erie results in large, warm, isothermal areas in the lake. Thermoclines exist only during the initial heating period in the western basin; from spring through to the period of maximum surface temperature in the central basin; and throughout the summer in the eastern basin. During the late fall the water in the entire lake is vertically isothermal. As winter progresses, the surface water temperature decreases to near freezing and stays that way until April when the new cycle of heating starts. In winter, after the temperature of the lake water has dropped to 4°C, the temperature gradient with depth is positive. Changes in the temperature structure other than from the normal heating and cooling cycle are caused by water of different temperatures coming into the lake (Detroit River), and by currents within the lake (upwelling on the north and south shores and doming of the thermocline off Long Point).

The consequence of vertical thermal stratification in terms of deep water oxygen depletion is different in each of the basins. In the absence of stratification in any one or all of the basins, vertical mixing processes will lead to replenishment of oxygen at depth. In summer the western basin is particularly sensitive to rapid oxygen depletion of bottom waters if periods of quiescent warm weather persist for several days. However, in deep areas where the hypolimnion is relatively thick (eastern basin), local de-oxygenation at depth is less serious since a larger volume of oxygen is available in the hypolimnetic layer.

2.1.2 Circulation and Water Movement

Knowledge of water circulation and diffusion processes enables one to make assessments of the movement and disposition of substances entering a lake. Direct measurements of lake water movements by drift objects or current meters provide information related to advection of substances within a lake, while the dilution of material levels by turbulent diffusion processes is best studied by tracking of artificial contaminants such as dyes. However, the combined effects of advection by lake circulation and of dilution by turbulent diffusion on dispersal of material entering the lake can be determined under some conditions by synoptic mapping of water properties. The latter approach will be referred to as "indirect" in the ensuing discussion.

Western Basin

Nearly all of the surface current studies reported in the literature are based on drift card or drift bottle observations. This includes the early work of Harrington (1895), and more recent studies by Wright (1955), Olson (1950), Verber (1953, 1955) and the Bureau of Commercial Fisheries. In addition, O'Leary (1966) reported on results of dye tracking experiments, based on dye releases from 20 stations near the mouth of the Detroit River.

The currents of the entire region are typically unsteady both in direction and in speed. Studies of the trajectories of drifting objects have shown that the currents in the western basin outside of the immediate influence of the Detroit River are correlated with the direction and intensity of the antecedent and instantaneous winds and with the fluctuations in water level known as seiches (Fig. 2.1.14). The circulation as presented here, is an idealized system since the transient movements have been averaged out. It is emphasized that significant deviations from the average flow are to be expected at any specific time.

The principal inflow of water into the basin is from the Detroit River. The influence of this river flow is dominant well out into the lake proper in a southeasterly direction. Upon occasion the Detroit River flow is detectable as far south as the Ohio shore.

Hartley *et al.* (1966) used conductivity and water temperatures at intermediate depths as "conservative" properties in tracing the movement of Detroit River water in the western basin.

On the basis of two extremely detailed surveys, they concluded that the main flow of the Detroit River was observed as far southeastward as the Ohio shore. Movements of water from the Maumee River eastward along the southern shoreline and subsequently northward along the west side of Bass Island were indicated. Thus, the dominant basin outflow was through the Pelee Passage on the Canadian side of the lake.

A returning northerly flow of water along the Michigan shore is developed under all winds, save those from the northwest, north and northeast, with the strongest occurrence being produced by southerly winds. A similar, though weaker return flow is observed along the Colchester shore during easterly and southeasterly winds.

The dominant flow near the Ohio shore is directed parallel to the shoreline in an easterly direction, except in the Bass Island region, where it is deflected to the north. The dominant flow from the western to the central basin occurs

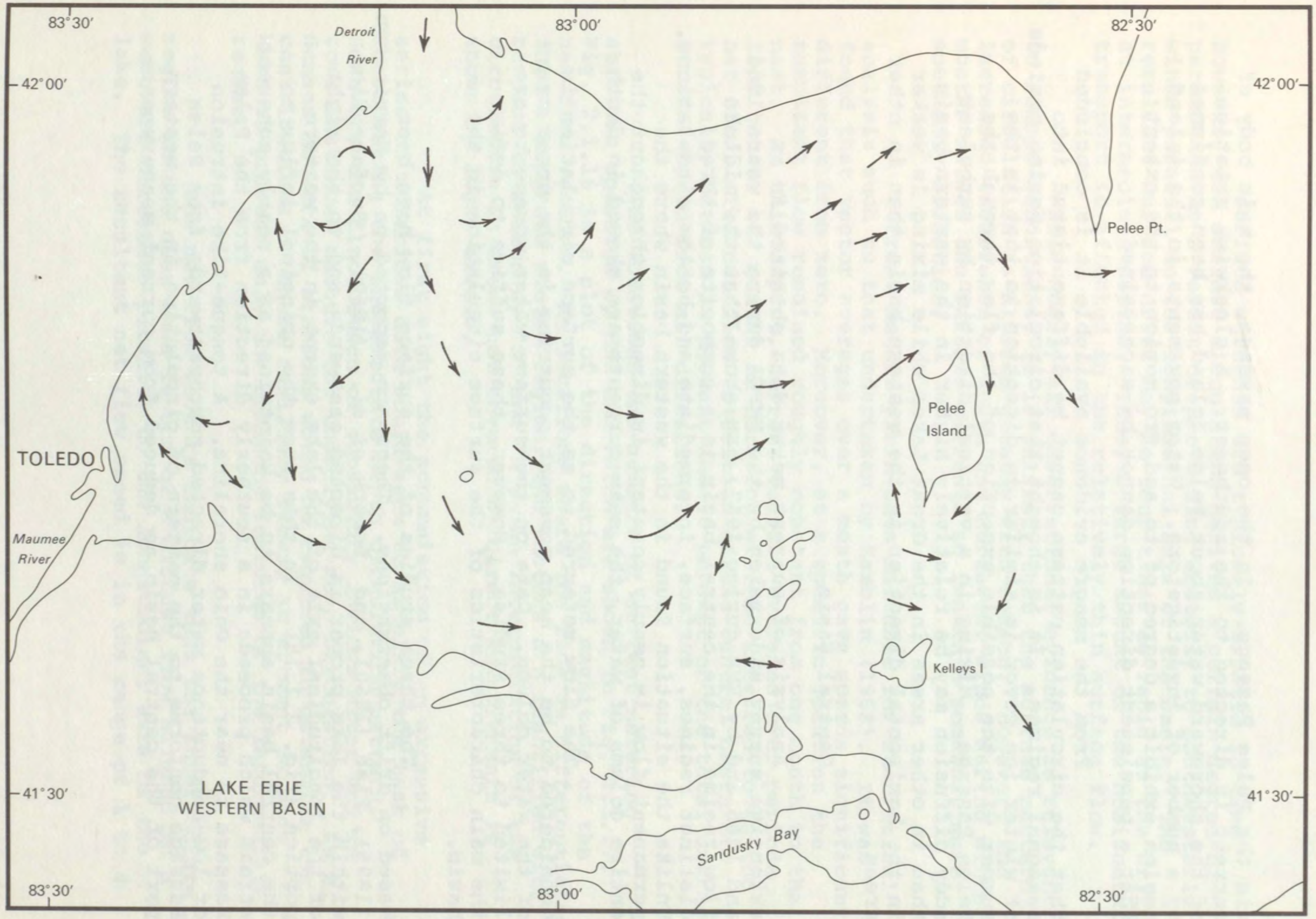


Fig. 2.1.14 Surface circulation in the western end of Lake Erie as inferred from drift card studies, 1892 - 1967.

via the Pelee Passage. In the open passage, the main body of current is directed to the southeast. A clockwise rotation of the shoreward water about Pelee Island has been confirmed by a number of investigators. Water movements in the island region exhibit a degree of to and fro motion to the extent that a persistent direction cannot be ascertained.

From the meagre evidence available it is concluded that the circulation pattern cannot be differentiated into seasonal regimes. It is thought that circulation during periods of winter ice cover is similar in direction to that in the summer with the possible exception of the flow through the Pelee Passage. Mixing in a vertical direction by turbulent eddy diffusion may be relatively higher in the western basin than in other areas in the Great Lakes while mixing is weaker in the horizontal direction in the western basin than in other areas.

Central Basin

Analysis of current meter data obtained in an extensive survey undertaken by the FWPCA during the years 1964 and 1965 and by EMR during 1967, has shown that the midlake flow regime in the central basin is a composite of three distinct regimes, surface, intermediate and bottom circulations. Unlike the situation found in the western basin where the permanent flow is nearly constant in direction throughout the entire column of water, the mean currents are skewed in depth.

The flow referred to as the surface circulation is considered to be the mean movement occurring in the upper metre of the water column. Data on the surface water movements are limited to three studies. However, these suffice to define the main characteristics of the surface circulation in the basin.

The three studies of the surface flow have been based on drift observations. These are reported on by Harrington (1895), Fish (1960), and Powers *et al.*, (1960). Surface flow within the lake proper is directed eastwards and to the right of the longitudinal axis of the lake except in the western portion (Fig. 2.1.15). In this area the principal influx to the central basin appears to be maintained as a nearly coherent stream which proceeds in a southerly direction from the Pelee Passage to near the Ohio shoreline. A tongue-like intrusion of low-conductance water directed southeastwards from Pelee Passage conforms to the pattern of circulation in the western part of the central basin as deduced from current measurements.

Surface currents are typically erratic in time. However, the surface circulation derives a certain degree of permanence as a result of prevailing westerly to southwesterly winds parallel to the longitudinal axis of the basin. The resultant surface drift may be four times as rapid as the drift at intermediate depths. Thus, a large amount of the horizontal transport is affected in the relatively thin surface flow.

While nearly all observational evidence is relevant to summer conditions, it is unlikely that the surface pattern of circulation is altered greatly with season. However, the increased occurrence of north and northwest winds during winter months causes the surface currents to run in a somewhat more southerly direction.

Current meters yield data suitable for statistical analysis such as that undertaken by Hamblin (1968). It was found that vector averages over a month gave speeds significantly different from zero. Moreover, at a specific location the resultant flow remained roughly constant from one month to the next. In this report, current vectors averaged over periods from two to six months in duration will be referred to as the net flow. The net flow velocities of the central basin are typically between 20 percent and 30 percent of the total average current speed from all directions.

The locations and numbers of current metering stations operated by EMR and FWPCA are shown in Fig. 2.1.17. Fig. 2.1.16 is a plot of the direction and magnitude of the net flow vectors. At locations where the flow is differentiated into a separate winter regime, the vectors are identified with respect to season by "S" and "W". An interpretation of the circulation in areas not covered by direct measurements is shown by light arrows.

At first sight the accumulation of an extensive series of numerical data would seem to simplify the task of interpreting the intermediate depth circulation pattern. However, the fluctuation of subsidiary inflows alter and in some instances obscure the underlying mean circulation. As a denser network of stations would be required to determine the contributions of these auxiliary flows, an attempt is made here to present only the dominant features of the intermediate regime.

The net flow vectors indicate that the intermediate regime in the open lake is one of a diffuse flow aligned in a westward direction parallel to the longitudinal axis of the lake. The resultant net flow speed is in the range of 1 to 3 centimetres per second (cm/sec) while the average current speeds, regardless of direction, are from 7 to 10 cm/sec. Speeds in excess of 54 cm/sec, although rare, have been measured in the open lake.

On the basis of measured values of the net flow at intermediate depths, and an extrapolation from a theoretically derived profile of current, the magnitudes of the surface and bottom drift can be predicted. The net surface drift is estimated by Hamblin (1968) to have an order of magnitude of 10 cm/sec and the bottom flow of 0.6 cm/sec.

Unexpectedly, there is little differentiation of the open lake flow by season. A meter situated at mooring station 6 at a depth of 10 metres yielded a resultant current, which was almost identical for the periods May to September, 1963 and October, 1963 to March, 1964.

Water movements at mid-depths in the western portion of the central basin, like those at the surface, are primarily directed to the southwest. The currents of the peripheral regions of the basin near the southern and northern shorelines, are less well-observed than those of the open lake. The presence of a clockwise flow between Pointe aux Pins and Pelee Point, is somewhat conjectural. Tracking of drogues conducted by EMR during the fall of 1967 demonstrated that nearshore currents conform to the configuration of the shoreline, but they neither confirm nor deny the gyral motion.

In summary, there emerges a conception of the open lake net flow regime which is one of a strong, wind produced, surface flow balanced by motion at intermediate and bottom depths. Near the shorelines the system of flow is complicated by the vertical circulation that must exist at the boundary.

Information on bottom currents in the central basin of Lake Erie has been obtained from a bottom drifting device known as the sea-bed drifter. As is the case with surface drift objects, the inference of water movement is clouded by uncertainties in the time and in the path travelled between release and recovery points.

A large number of sea-bed drifters was released by the FWPCA in the summer of 1965, in a pattern which, while covering the central basin, was weighted in favour of the inshore waters along the southern shoreline. Bottom currents interpreted from the data by Hamblin (1968), are presented in Fig. 2.1.17 along with current meter station positions discussed later in the text.

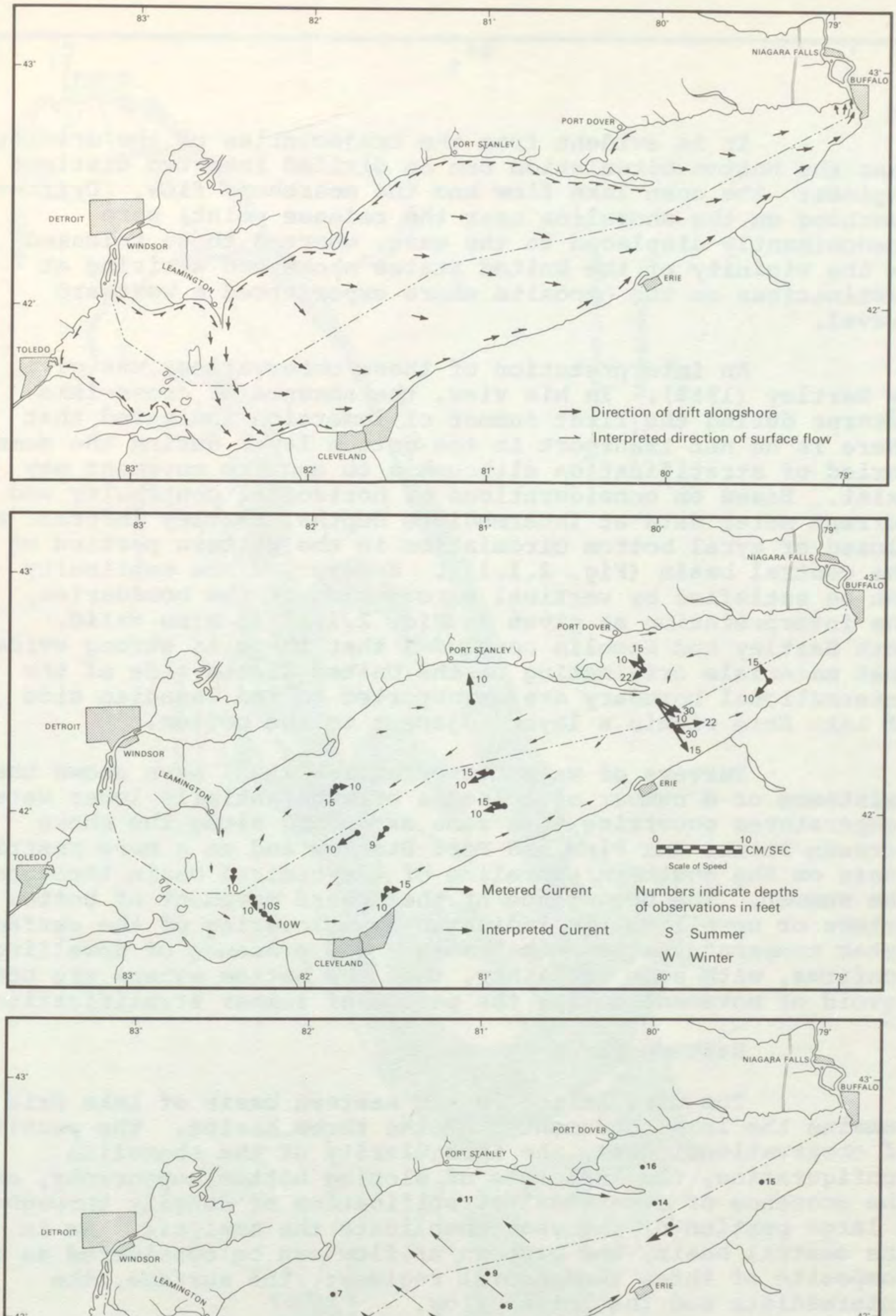


Fig. 2.1.15, 2.1.16, 2.1.17 Dominant features of the surface, intermediate and bottom circulation in the central and eastern basins of Lake Erie.

It is evident from the trajectories of the drifters that the bottom circulation can be divided into two distinct regimes: the open lake flow and the nearshore flow. Drifters beaching on the shoreline near the release point, were predominantly displaced to the east, whereas those released in the vicinity of the United States shore and arriving at destinations on the opposite shore experienced a westward travel.

An interpretation of these observations was given by Hartley (1968). In his view, the absence of cross-lake returns during the first summer of immersion indicated that there is no net transport in the bottom layer during the summer period of stratification although a to and fro movement may exist. Based on considerations of horizontal continuity and current meter data at intermediate depths, Hartley inferred a closed or gyral bottom circulation in the western portion of the central basin (Fig. 2.1.18). However, since continuity can be satisfied by vertical circulation at the boundaries, the interpretation as given in Fig. 2.1.17 is also valid. Both Hartley and Hamblin concluded that there is strong evidence that materials originating on the United States side of the international boundary are transported to the Canadian side of Lake Erie within a layer adjacent to the bottom.

Surveys of water temperatures (EMR) have shown the existence of a number of episodes of substantially lower water temperatures occurring in a zone extending along the shore between Pointe aux Pins and Port Stanley and on a more restricted basis on the southern shoreline of the central basin throughout the summer. The occurrence of the upward movement of bottom waters or upwelling, is indicated by a lowering of the surface water temperatures near the shore. The presence of upwelling confirms, with some certainty, that the bottom waters are not devoid of movement during the period of summer stratification.

Eastern Basin

The circulation in the eastern basin of Lake Erie remains the least documented of the three basins. The paucity of observational data, the irregularity of the shoreline configuration, the influence of sloping bottom topography, and the presence of a vertical stratification of density throughout a large portion of the year complicate the analysis. As in the central basin, the pattern of flow can be considered as a composite of three fundamental regimes: the surface, the intermediate and the bottom flow.

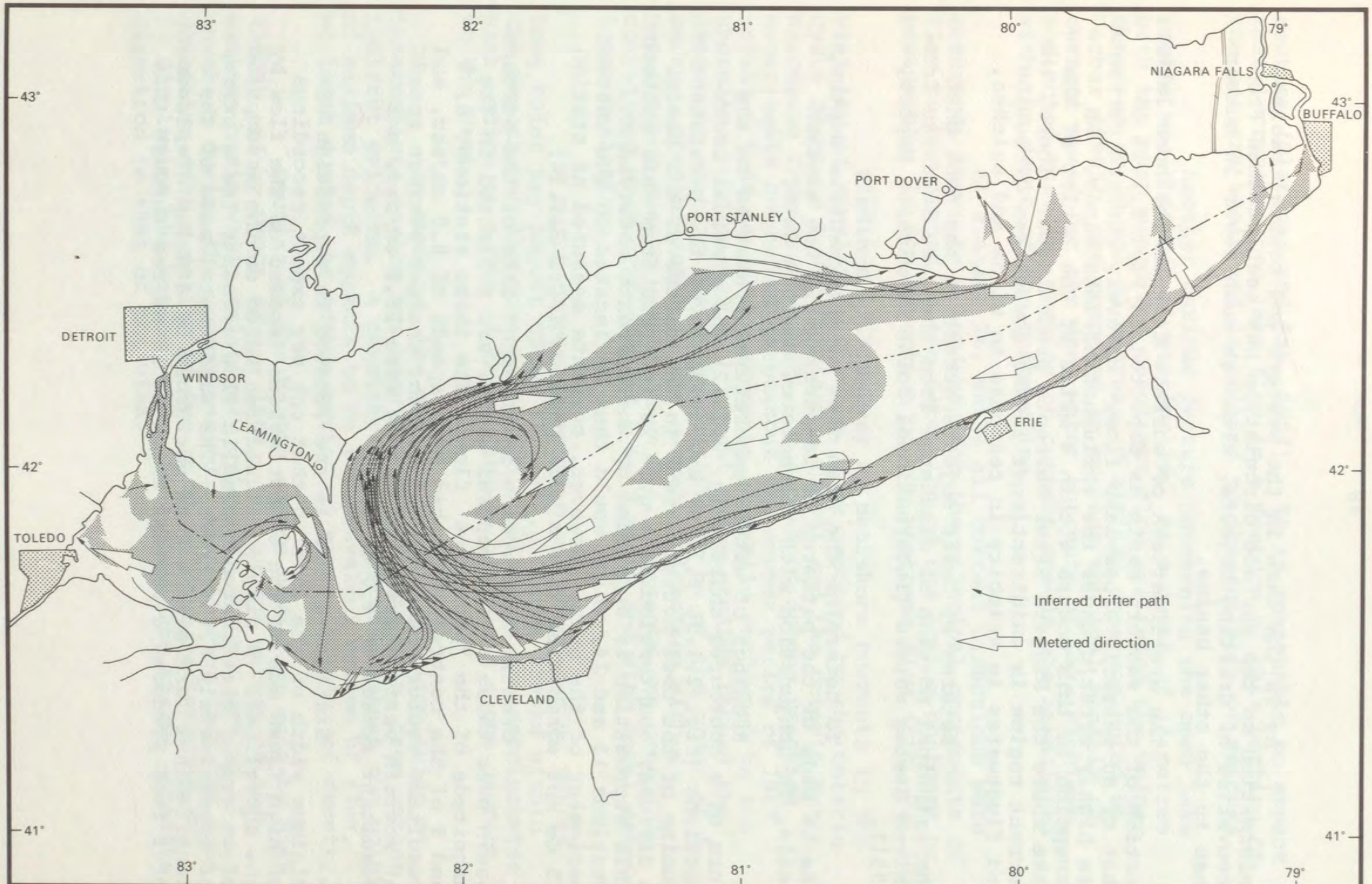


Fig. 2.1.18 Bottom circulation based on drifters and current measurements.

As is the case in the western and central basins, information on the surface circulation has been deduced from recoveries of drifting objects, although much fewer in number than in the other basins.

The areal pattern of surface flow in the open lake portion of the eastern basin as depicted in Fig. 2.1.15 is that of an easterly cross-lake flow. However, surface currents are highly erratic under the influence of lake winds. An exception to this occurs within 4 miles of the outlet of the lake where the Niagara River currents predominate. There, the current regime is unidirectional in the downstream direction and fluctuates in velocity in response to winds and seiches.

Returns of drift objects attest to the fact that the principal portion of discharge from the lake is drawn from United States waters (International Joint Commission Report, 1951).

To determine the mean flow at intermediate depths, use is made of the patterns of temperature in the eastern basin, in conjunction with the metered current data.

Readings of water temperatures presented in the form of a contoured chart (Fig. 2.1.12) and vertical cross-sections (Fig. 2.1.9, 2.1.10) are evidence of the persistent doming of the cool bottom waters in the centre of the basin. A diffuse, counterclockwise gyre is inferred from this pattern. This supposition is supported by the currents observed at stations 13 and 14, which would thus be located on the western perimeter of the gyre. However, currents measured at station 15 do not agree with this simple pattern (Fig. 2.1.16).

Greater mean speeds in the open lake of the eastern basin over those of the central basin, are reflected in the magnitude of the "permanent" flow. The three stations, 6, 8 and 9 of the central basin had mean speeds of 8.8 cm/sec, and resultant vector speeds of 2.1 cm/sec, whereas average speeds at eastern basin stations 13 and 14 were 16.6 cm/sec, and resultant speeds of 4.0 cm/sec.

Stations 13 and 14 are located in a position of minimum width of the lake so that one may expect recordings of high flows due to the constrictions imposed on the flow by the shorelines. A simple calculation based on the assumption of an evenly distributed hydraulic flow accounts for a current of approximately 0.05 cm/sec. The fundamental mode of the longitudinal lake seiche when perturbed by a setup displacement of 1 foot produces a current which is 15 cm/sec through this section (Platzman and Rao, 1964). It is reasonable to expect that increased open lake flow is a feature of this portion of the eastern basin and is related to the activity of seiches.

Another curious feature concerning the open lake regime was observed at station 14. At a depth of 15 metres both the mean speed and resultant flow are twice the values observed at 10 and 30 metres. A similar case was noted by Verber (1965), who compiled an average vertical profile of current speed for the deep water currents of Lake Michigan, and noted that the peaking of current speeds was associated with the depth of the thermocline.

At station 16, while all current directions were observed, there is a tendency for the principal components of flow to be aligned in the direction of the bottom contours or, presumably, in the direction of the upstream flow (Fig. 2.1.17).

Findings of a survey of nearshore currents in the vicinity of Nanticoke, Ontario, were reported by the Ontario Hydro Electric Power Commission (1968) and the Ontario Water Resources Commission (1968). A series of drogue tracking experiments conducted throughout the summer period of 1967 revealed that nearshore currents generally conformed to the shoreline configuration. Current meter studies showed the nearshore monthly resultant currents to be of the order of 5 cm/sec, predominantly in the easterly direction with a persistence factor greater than 0.5. Currents are generally correlated over distances of 2 to 3 miles and with local water level variations.

A multi-drogue experiment was conducted by EMR in Long Point Bay August 15 to 17, 1967. Drogue tracks within the bay showed the formation of clockwise and counterclockwise back eddies in spite of the influence of a long shore current to the east.

In summary, the general pattern of circulation at intermediate depths has been deduced, in the main, from rather indirect evidence. A counterclockwise rotation about the point of maximum depth appears to be the prevalent system of flow, at least during the summer period of stratification of density.

Studies of the bottom regime have been made by Fish (1960) and by FWPCA during 1964. The bottom waters of the eastern basin while relatively quiescent are not devoid of movement during the summer period. Wind blowing from the same direction over a period of two to three days is instrumental in displacing the bottom waters at a slow rate in the opposite direction to that of the wind.

At station 12 (Fig. 2.1.17), currents between May and October, 1964, were aligned perpendicularly to the gradient of the local bottom topography. A typical current speed at this location is about 6 cm/sec. The return of three seabed drifters, all of which were released on the southern shore of the central basin and which arrived at destinations on the northern shoreline of the eastern basin, is suggestive of a system of cross-lake flow from south to north.

Diffusion

Dye diffusion experiments in 1963 conducted by Csanady (1964) within 1.3 miles of the Colchester shore are one of the few reported works which yield a quantitative measure of the effective redistribution of materials in the vertical and in the horizontal directions by turbulent mixing processes. Values derived for absolute vertical eddy diffusivity (3 to 30 square centimetres per second (cm^2/sec) are in agreement with those given by Bowden (1965) for the Mersey estuary, U.K., and are somewhat higher than values obtained in Lake Huron and under similar conditions by Csanady. On the other hand, the coefficients of relative horizontal eddy diffusion (800 - 2,600 cm^2/sec) are somewhat less than the values found for Lake Huron. Csanady attributed the relatively high vertical diffusivity in Lake Erie to the shallowness of the bottom, and to the lack of strong temperature stratification.

An occurrence noted on one of eight trials was that a barrier or "floor" to vertical diffusion developed at an intermediate depth. The effective vertical migration of substances was halted at this level while the horizontal spread was accelerated. Further, the horizontal transport of materials was increased by current meandering and the to and fro motion of the water. Therefore, Csanady's values for the relative horizontal diffusivity may be considered as the lower limits for turbulent mixing processes in the basin.

At a station 4 1/2 miles southwest of Colchester, Okubo and Farlow (1967) deduced estimates of "absolute diffusion" coefficients in the horizontal direction. By considering the displacements of groups of drogues at successive intervals of time, they derived values in the order of 4.1×10^4 cm^2/sec which were an order of magnitude higher than the relative diffusion measurements of Csanady.

Okubo and Farlow (1967) also conducted diffusion experiments in the central basin on two occasions in 1964. They used an extensive array of drogues at a distance of 1 1/2 miles from the shore at Cleveland, Ohio. By repeatedly measuring the time behaviour of the areal spreading of the drogue pattern from their initial positions, they found an effective horizontal diffusivity of 3.3 x 10^4 cm^2/sec, a value which was an order of magnitude larger than that obtained in the work of Csanady but similar to their work referred to earlier. They have accounted for this by the fact that their observations have included the effects of the very large eddies which are probably causing the meandering of dye plumes that Csanady observed.

Models of Lake Circulation

Models of lake circulation can provide not only a means for interpolation of observational data on currents, between points of measurement, but it can also produce a deterministic basis for the estimation of lake currents from easily measured shore-based factors such as wind.

Perhaps the most extensive analysis of the dynamics of Lake Erie has been accomplished by the numerical hydrodynamical modelling technique of Platzman (1963). His dynamical equations account for the action of gravity, wind stress, the earth's rotation, a linearized bottom friction and the actual bottom and shoreline configuration. Successive numerical integrations of his equations yielded values of water levels and currents at six hourly intervals based on an input of wind stress over the lake. A high degree of correlation between observed and computed lake set-up was found although verification of predicted currents has yet to be attempted.

A purely analytical solution of the time-invariant dynamical equations has been obtained by Birchfield (1967) for the case of a rotating circular model Great Lake with a parabolic profile of depth, homogeneous water mass, and a realistic mathematical model of bottom friction under the action of various types of wind fields. His result is applicable to the circulation produced by a uniform wind field and may be compared to the time-averaged current vectors interpreted by Hartley and presented in Fig. 2.1.18. Distinguishable in the theoretical result is a clockwise whirl on the upwind side of the lake, a counterclockwise whirl on the downwind side, an intensification of the currents on the inshore side of these gyres and a diffuse circulation in the lake centre in a direction to the right of the wind.

A much simpler theoretical analysis of the vertical profile of currents in the central and western basins has been undertaken by Hamblin (1968) who assumed a constant surface wind stress, a representation of bottom stress identical to that used by Birchfield, and no net transport. Theoretically derived profiles are compared to those of Nomitsu and Takegami (1934) who assumed a different system of bottom friction. Agreement of both models with observed surface and intermediate currents for the case of steady southwest winds is encouraging. Accordingly, the model has been used to predict the magnitudes of the steady surface and bottom currents.

The effect of the Coriolis force on Lake Erie currents has been investigated by rotating laboratory models of the lake. Rumer and Rodson (1968) have demonstrated that under rotational forces only, the Detroit River water is maintained as a relatively intense narrow stream along the southern shoreline of the lake and through Pelee Passage.

While the theoretical approach is not too far advanced as yet, the early results are promising enough to indicate that this approach will yield a more complete knowledge of lake water movements.

Discharge and Residence Time

If the inflow to Lake Erie were uniformly distributed (90 percent is derived from the Detroit River flow), one could estimate the time taken for replacement of waters. At the average discharge rate of 200,000 cfs or 5.6 x 10^6 litres/second (Rainey, 1967) approximately four years of continuous flow would be required for flow-through of all but 10 percent of the inflowing waters (Hamblin, 1968). However, in the actual environment, due to circulation patterns the residence time is probably at least twice as long for water in the central and northern parts of the lake and perhaps shorter for the water caught up in the main flow along the south shore to the Niagara River. The interpretation of this flow-through rate in terms of self-purifying time for the lake, is misleading. Four years is obviously a minimum period for flushing of 90 percent of the lake waters.

2.2 SEDIMENTOLOGY

Study of the sediments of a lake can provide knowledge about its nature and evolution. In areas of deposition, the sediment column can be interpreted as a history of the lacustrine environment. This is particularly important since the sequence of fossils and other organic and inorganic materials entombed in sedimentary strata can indicate past changes and present trends in eutrophication, water levels, climate, lake chemistry and aquatic biota. Sedimentary processes involving erosion from the drainage basin and shore, dispersal by lake currents, deposition and diagenetic alterations in the lake bed, are an integral part of the lake environment. The continuation of these processes through time, leads to an expansion and siltation of the lake basin; one manifestation of natural lake aging. Knowledge of these processes will enable us to predict the path of travel and final resting place of particulate pollutants. Decomposition of organic material and other chemical changes can release nutrient chemicals to the overlying lake waters. Because some of the effects of these processes are detrimental to water quality, they warrant study and should be understood as part of any pollution abatement program.

The geological development of the Lake Erie basin is summarized in Section 1.1.3. The specific role of sediment in water pollution is considered in Section 3.1.4. In this section the nature, origin and distribution of sediments are described.

Contributions to the sedimentology of Lake Erie have been made over a lengthy period of time. Early navigation charts published by the governments of Canada and the United States defined the bathymetry of the lake basin and gave the bottom character at selected locations. Later, Pegrum (1929) provided the first sediment distribution chart of the central and eastern basins based on the data of a 1928-29 limnological survey (Fish, 1929). In 1933 and 1936, Kindle, published the results of sand and gravel surveys around Pelee Island and Pelee Point in connection with the study of erosion of the Point. The vertical textural variations in sediment cover and bedrock topography in the western basin, were studied by Ross (1950). Shore zones of the central basin were studied by Wood (1951) and Pincus (1953 and 1960). The most extensive and detailed study of modern bottom sediment distribution, was undertaken in the Ohio sector of the lake by Verber (1957), and Hartley (1960, 1961a, 1961b). More recently, Herdendorf (1968) described the geologic setting and contemporary sedimentation in the southern portion of the western basin. Lake-wide investigations have been published by Kramer (1961); Benson and MacDonald (1962); Kick (1962); Morgan (1964); Lewis (1966) and Lewis *et al.* (1966).

2.2.1 Lake Morphology

Although Lake Erie is noted for shallow depths and gentle bottom relief, the lake bed is sub-divided into distinct basins, illustrated in Fig. 1.1.1 and 2.2.1. The sub-basins are clearly apparent in Fig. 2.2.1 which portrays the inferred bathymetry of early Lake Erie before the basins were partially filled and obscured by mud sedimentation. The eastern, central and Sandusky basins are separated by sand-veneered ridges of

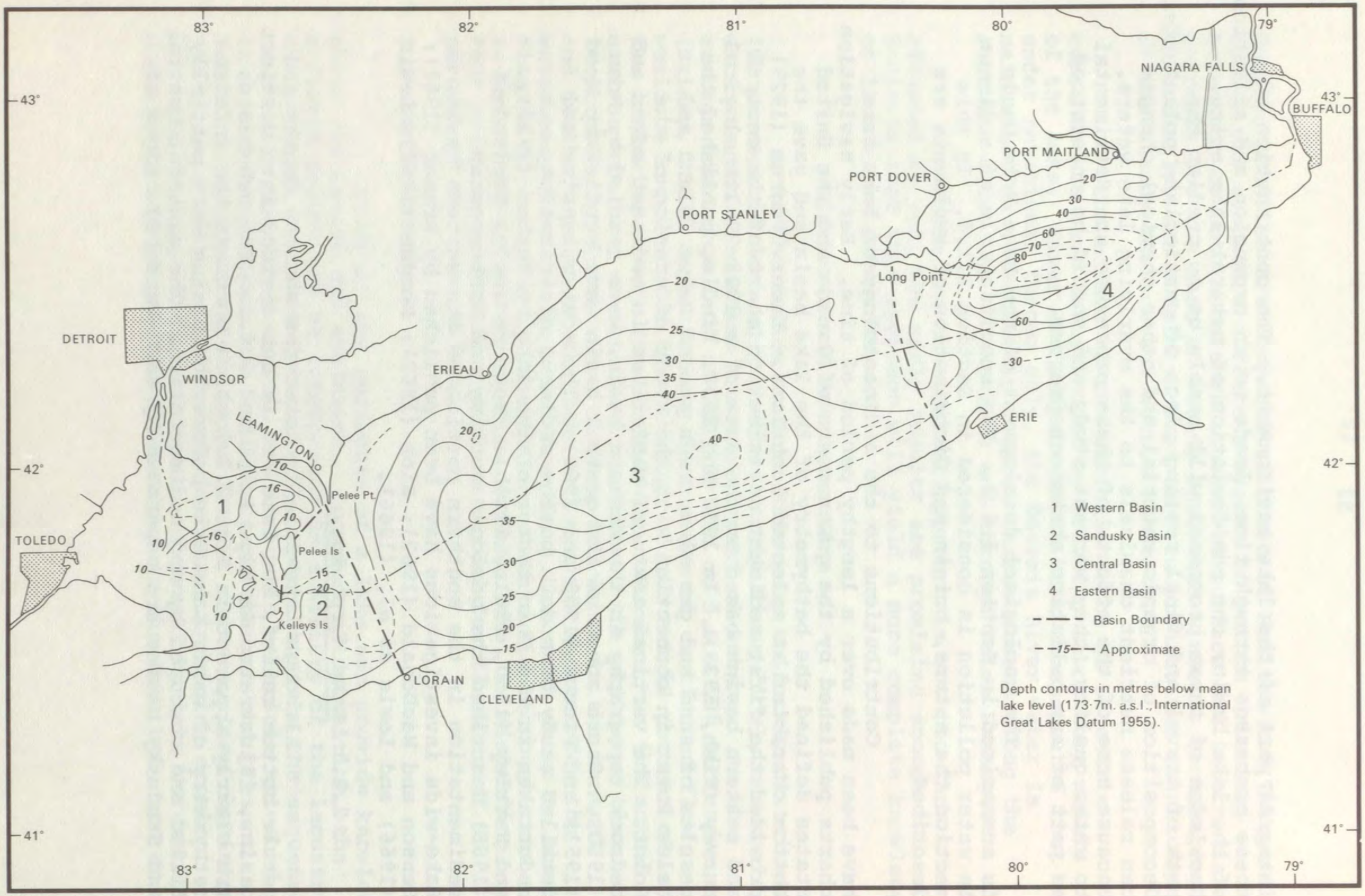


Fig. 2.2.1 Topography of Pleistocene deposits.

glacial clay deposits which cross the lake between Long Point and Erie, Pennsylvania and Point Pelee and Lorain, Ohio, respectively. The western basin is separated from the remainder of the lake by a chain of bedrock islands - Pelee, Middle and Kelley's trending south to southwest from Point Pelee. Although the Sandusky and central basins are considered as morphological and sedimentological entities in this section, they are jointly referred to as the central basin in most other sections of this report.

2.2.2 Shoreline

Much of Lake Erie is bounded by shore bluffs undergoing active erosion. Because the eroded shore materials, largely silt and clay sizes, probably contribute most of the sediment to the lake, a brief description of the shoreline is presented here.

Canadian Shore

The bedrock is responsible for the numerous irregular headlands and shoals which characterize this shore. A thin mantle of till, 3 to 10 feet thick, covers the bedrock. In places, particularly between Pt. Abino and Port Maitland, the till is buried beneath stabilized sand dunes. The north and west shores of Long Point Bay are bordered by strong cliffs rising 120 feet above the lake at Turkey Point. The cliffs consist of varved clay and some clay till topped with lacustrine sand. Turkey Point and Long Point are recent sand spits with low ridged shorelines.

The north shore of the central basin is clearly divided into two segments, by three spits in which sands are presently accumulating - Long Point, Point aux Pins and Pelee Point. Between these features, the shore is indented and marked by dramatic vertical bluffs rising up to 125 feet above the lake. Throughout, the bedrock surface is several tens of metres below lake level; the bluffs are composed of two till sheets overlain with bluff lacustrine silt and sand. Just west of Long Point the lacustrine sands constitute the entire bluff and provide material for dunes rising 175 feet above the lake (Sand Hills, Norfolk County). Westward to Port Burwell, lacustrine clay sediments are commonly exposed in the bluff.

The Ontario shore west of Pelee Point to the Detroit River is a low bluff up to 25 feet high. At Colchester it is composed of silty and sandy till. Pelee Point is a modern spit built of sands eroded from shore bluffs both to the east and west. The low ridged eastern and western shores impound marshy ground between them and meet at a point projecting southward into the lake.

United States Shore

Most of the Michigan and Ohio shore of the western basin is low and marshy, and lacks a shore cliff except for the bold headland composed of limestone and capped with a thin till cover south of the island area. All stream valley mouths are flooded with lake water; this shore has clearly submerged in geologically recent time. The south shore of the central basin is a wave-cut bluff like that along the north shore except that it differs in height and composition. Bluff heights are generally lower, 65 to 80 feet east of Cleveland, 80 feet between Conneaut, Ohio, and Erie, Pennsylvania and commonly less than 65 feet along the remaining shore. Siltstone and shale bedrock outcrops near lake level and forms the basal bluff structure at several locations. The bedrock forms much of the lake bottom out to one mile offshore east of Vermilion, Ohio. Presque Isle at Erie, Pennsylvania is a modern sand spit with low-ridged shoreline.

Eastward from Erie, the south shore takes the form of a bluff ranging from several feet up to 100 feet above the lake. The basal section of the bluff is composed of gently southward dipping, thin-bedded shales and siltstones with occasional limestone interbeds. The rock surface lies within a zone of 50 feet above lake level. Unconsolidated deposits commonly composed of till, overlain with bluff lacustrine silt and sand, mantle the rock surface and form the upper portion of the shore cliffs.

2.2.3 Bottom Deposits

Bedrock

Bedrock, largely siltstone and shale, commonly outcrops on the lake bottom in shallow water and along the south shore of the central and eastern basins. The distribution of bottom deposits is illustrated in Fig. 2.2.2. In eastern Lake Erie, the bedrock contains numerous carbonate interbeds. A belt of blocky limestone outcrops along the north shore of the basin, between Buffalo and Port Dover. In the western basin all of the islands and most shoals are surrounded by limestone or dolomite outcrops.

Glacial Deposits

Glacial deposits are widely exposed on the lake bed adjacent to the shore zone in water depths up to 20 metres. For the most part the glacial deposits are lake clays and clay tills. They are characterized by a red colour (eastern half

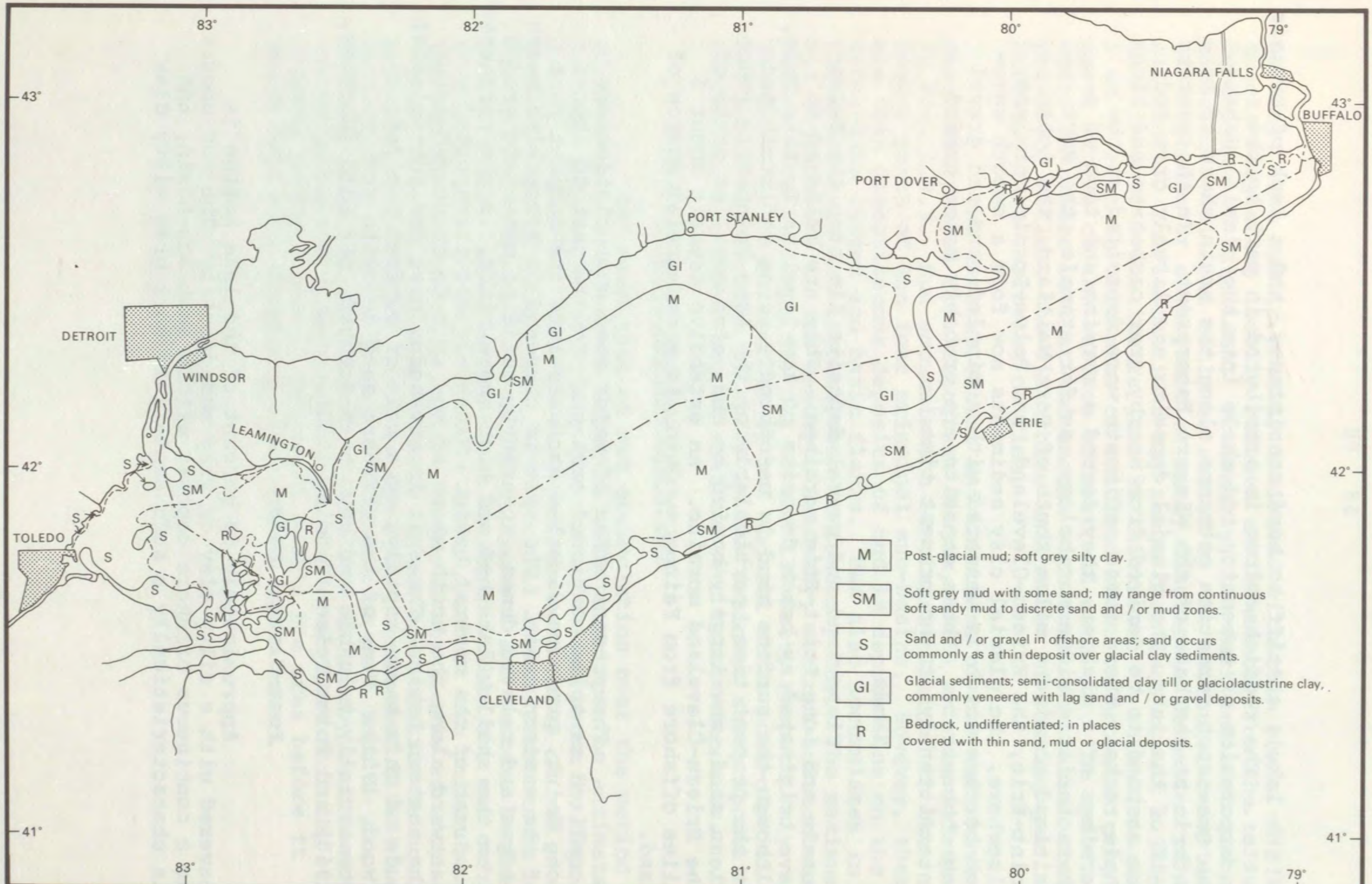


Fig. 2.2.2 Distribution of bottom sediments.

of the lake), a stiff to hard consistency, and a lack of organic matter. The reddish colour is attributed in part to the incorporation of Queenston red shale into the glacial debris. The Queenston formation outcrops along the south shore of Lake Ontario at the base of the Niagara Escarpment. In the western half of the lake, the glacial deposits are largely grey and are assumed to be derived from nearby grey carbonate and black shale rocks. Where these sediments were deposited at the terminus of a glacier, they formed a moraine and took on a characteristic ridge morphology, as for example, the Port Maitland moraine 6 miles south of Port Maitland, the Long Point-Erie, the Erieau-Cleveland, and Pelee-Lorain moraines. Elsewhere, the glacial clay sediments now form a smooth wave-cut terrace which is veneered with a rippled sand and gravel lag concentrate. These deposits are probably being eroded intermittently at the present time.

Sands

Clean sand and gravel deposits lie atop the Pelee-Lorain and Long Point-Erie moraines. They are believed to have originated as beach deposits of low-level early Lake Erie, although the surface sand is undoubtedly being redistributed at the present time, particularly on the Long Point-Erie ridge. Clean sand, now largely buried by mud, also overlies parts of the Erieau-Cleveland moraine. An extensive deposit about 5 miles offshore from Fairport, Ohio, is a commercial source of sand.

The present areas of major sand accumulation are localized as spits mentioned earlier. The largest of these, Long Point, projects 25 miles eastward into the deepest part of the eastern basin. The spit is composed of successive beach ridges and related dunes, apparently built of materials eroded from the shallow lake bed and high shore bluff, in the northeast quadrant of the central basin. Materials are transported eastward along the south shore of the spit to be dumped into the eastern basin. The spit is advancing over the post-glacial muds of this basin rapidly, at a rate of 23 feet per year (Wood, 1951). Many of the offshore sand deposits are commercially valuable and have been dredged, off Ohio (Hartley, 1960) and Point Pelee (Kindle, 1933).

Post-Glacial Muds

Approximately 58 percent of the lake bottom is covered with a silty clay or clay mud deposit. The mud occurs as a continuous offshore deposit within each sub-basin, and is characteristically a soft semi-fluid dark grey silty clay or clay. The mud is crudely laminated with thin bands of black specks suggesting locally reduced environments from the deposition of sulphides. Presumably, the dark sediment and reducing conditions could be caused by the bacterial reduction of sulphates or authigenic or early diagenetic formation of sulphides. The laminations may range from less than 1 millimetre (mm) to over 1 centimetre (cm) in thickness. A thin microzone 1 mm or more in thickness of oxidized brown or brownish grey ooze, occurs on the surface of most mud samples. The mud-water interface is flat and smooth with small depression cones which may reflect the disturbing influences of venting gas bubbles, worm burrowing or fish.

The lateral extent and thickness of the muds have been interpreted from echograms (Lewis, 1966) and are illustrated in Fig. 2.2.3. Mud accumulation is clearly limited to the deeper parts of the four principal sub-basins. However, there are thin discontinuous deposits of mud in depressions on the cross-lake ridges and basin flanks. Mud also accumulates in protected bays and lagoons such as Sandusky Bay. The maximum mud thicknesses in the western, Sandusky, central and eastern basins, are at least 16, 33, 65 and 130 feet, respectively. The probable major sources of mud and all other post-glacial sediments are erosion of soils in the drainage area, shoreline recession, and reworking of shallow lake bottom deposits.

2.2.4 Rate of Mud Sedimentation

The mean rate of mud accumulation over the period of Lake Erie's existence (about 12,000 years) can be estimated for any locality by dividing the mud thickness shown in Fig. 2.2.3, by 12,000. In this way, maximum mean rates of mud accumulation of .016, .031, .067 and .13 inches/year can be derived for the western, Sandusky, central and eastern basins, respectively. Radiocarbon dates obtained within the mud column indicate rates of .012 and .024 inches/year at two points in the western and central basins, respectively (Lewis *et al.*, 1966). However, the present rate of mud accumulation is not necessarily indicated by these figures. Herdendorf (1968) has collected up to four inches of sediment on reef tops in the western basin within a single year while in nearby regions the accumulation was almost negligble. It is implied that the trapped sediment was in transport across the area before it would have been deposited elsewhere in quiet water.

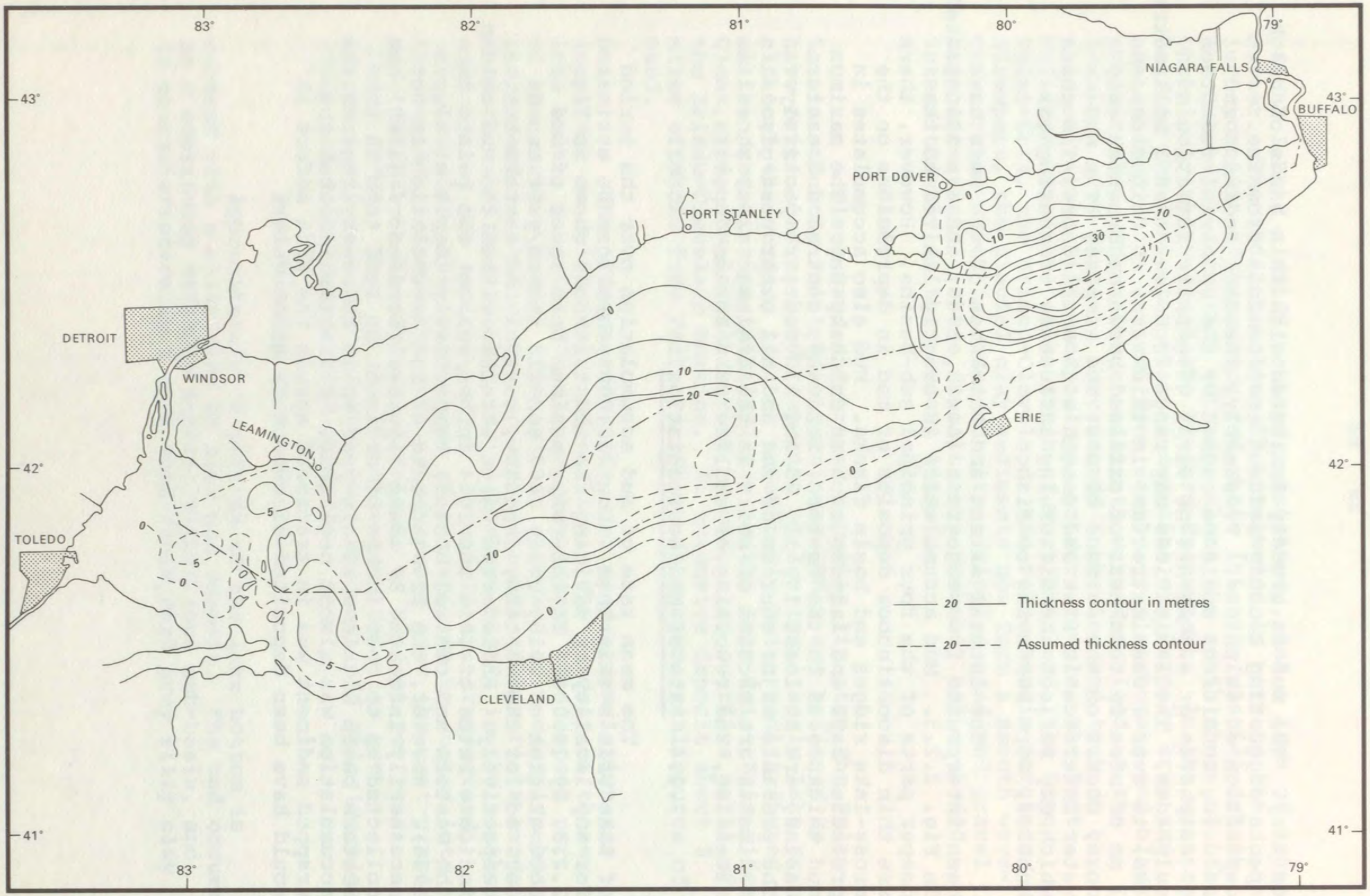


Fig. 2.2.3 Isopach map of recent mud deposits in Lake Erie.

2.2.5 Characteristics of Offshore Sediments

Sediment Particle Size

The particle size grade percentages have distinct values for the central areas of each of the sub-basins sampled in Lake Erie (Kemp and Lewis, 1968). The central basin deposits are largely clay, whereas the eastern and western deposits contain nearly equal proportions of silt and clay. The distribution of sediment mean particle diameter, expressed in phi units where phi = $-\log_2$ (mean particle diameter in millimetres), throughout the lake, is given in Fig. 2.2.4. Close to the cross-lake ridges, between basins and near the shore-mud boundary, particle diameters rise significantly, indicating a mixture in the basin mud of coarse material probably derived from the sand and silt sediments known to occur in shallow water. The admixture in the surface muds is particularly evident west of the Long Point-Erie moraine. The sand source may be the moraine itself or a number of small sand deposits north of Conneaut described by Hartley (1963).

Mineralogy

Micaceous minerals (biotite, muscovite, chlorite), true clay minerals (kaolinite, illite, montmorillonite) as well as quartz, feldspar, calcite and dolomite, have been identified in the surface sediments of Lake Erie by Cuthbert (1944), Kramer (1961), Lewis (1966), and Herdendorf (1968), using x-ray diffraction methods. Kramer (1961) states that all sediments high in clay content contain sulphide ions. Kemp and Lewis (1968), determined clay mineral contents in selected Lake Erie sediments and found that clay minerals comprised up to 67 percent of mud sediment. The clay mineral contents were directly proportional to the percentage of sample less than 2 microns (μ) in diameter. A relatively high degree of maturity is indicated for these "young" post-glacial sediments. The clay minerals probably originated by erosion from shale bedrock and were recycled through glacial and post-glacial processes to their present site. The glacial deposits are rich in calcite and dolomite; post-glacial muds contain negligible carbonate except near their boundaries with glacial deposits.

2.2.6 Redox Potential

Considerable variation in oxidation reduction potential (Eh) was observed from station to station and with depth of burial during a September 1967 cruise (Kemp and Lewis, 1968). The Eh varied from + 0.288 to - 0.147 volts. At the

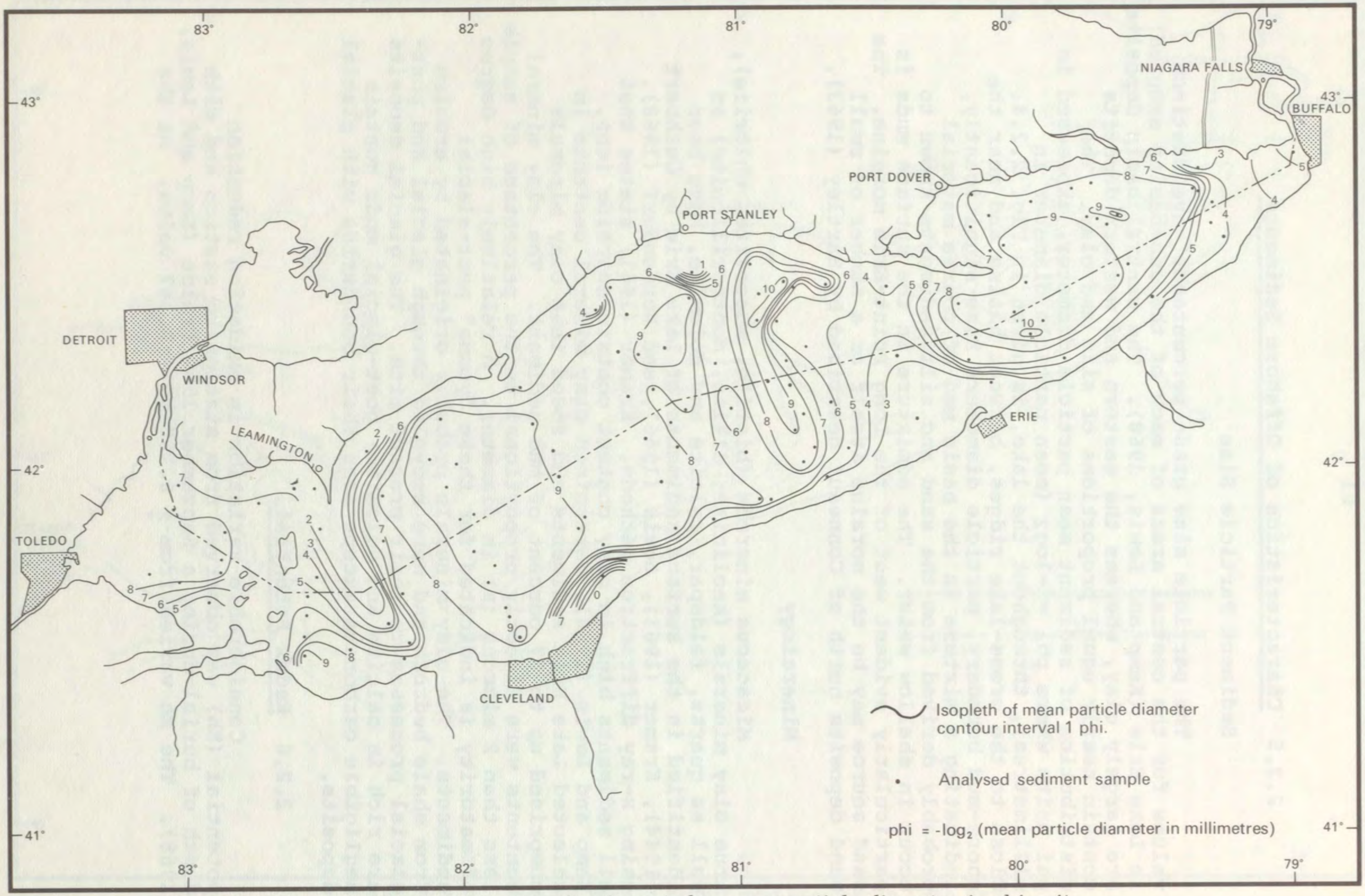


Fig. 2.2.4 Distribution of sediments by mean particle diameter in phi units.

majority of stations the Eh decreased with depth of burial. The average depth in the sediment at which Eh changed sign, was calculated to be 0.32 inches, thus for most stations oxidizing conditions prevail within the top centimetre of sediment. The change from oxidizing to reducing conditions in the sediment was paralleled by a distinct change in colour. The oxidized sediments were a pale grey or brown colour whereas the reduced sediments were black. Large negative potentials were encountered in surficial sediment at one station in the central basin.

The thin oxidized microzone on the mud surface is believed to be rich in ferric hydroxide and ferric phosphate. This microzone forms a chemical barrier that keeps phosphate ions in the reduced sedimentary layer below from going into solution, and also assimilates material falling to the bottom. However, when the microzone is destroyed, as is indicated by the observed black sediment colour and negative Eh values, phosphate and ferrous ions may be recycled into the water mass from the sediment below. This is likely to occur in summer in the central basin when the water is thermally stratified and oxygen is depleted in the hypolimnion.

Organic Matter

Percent organic carbon in Lake Erie sediments ranged from 0.23 to 3.60 for all measurements and from 1.67 to 3.05 in the surface millimetre (Kemp and Lewis, 1968). Organic carbon contents were lower on the average in Lake Erie than in Lake Ontario. This is attributed to a greater dilution with coarser grained non-organic sediment particles in Lake Erie. The organic carbon content is inversely proportional to the grain size of Lake Erie sediments. Fig. 2.2.5, shows the relationship between organic carbon and percentage of sediment less than 2 μ in diameter. Kick (1962) also found a positive correlation between organic matter, clay content and water content in Lake Erie's surficial sediments. The areal distribution of organic carbon is associated in part with the lake bed morphology. The greatest carbon concentrations are found in the deep central portions of each sub-basin. The average organic carbon contents in percent dry sediment in the western, Sandusky, central and eastern basins were 2.39, 2.35, 3.24, and 2.20, respectively.

The relationship between organic carbon, chlorophyll pigments and depth of burial in the sediment, indicates that most of the chlorophyll, presumably originating with plankton in the surface water, is decomposed by the time it reaches the lake bottom (Kemp and Lewis, 1968). Further decomposition

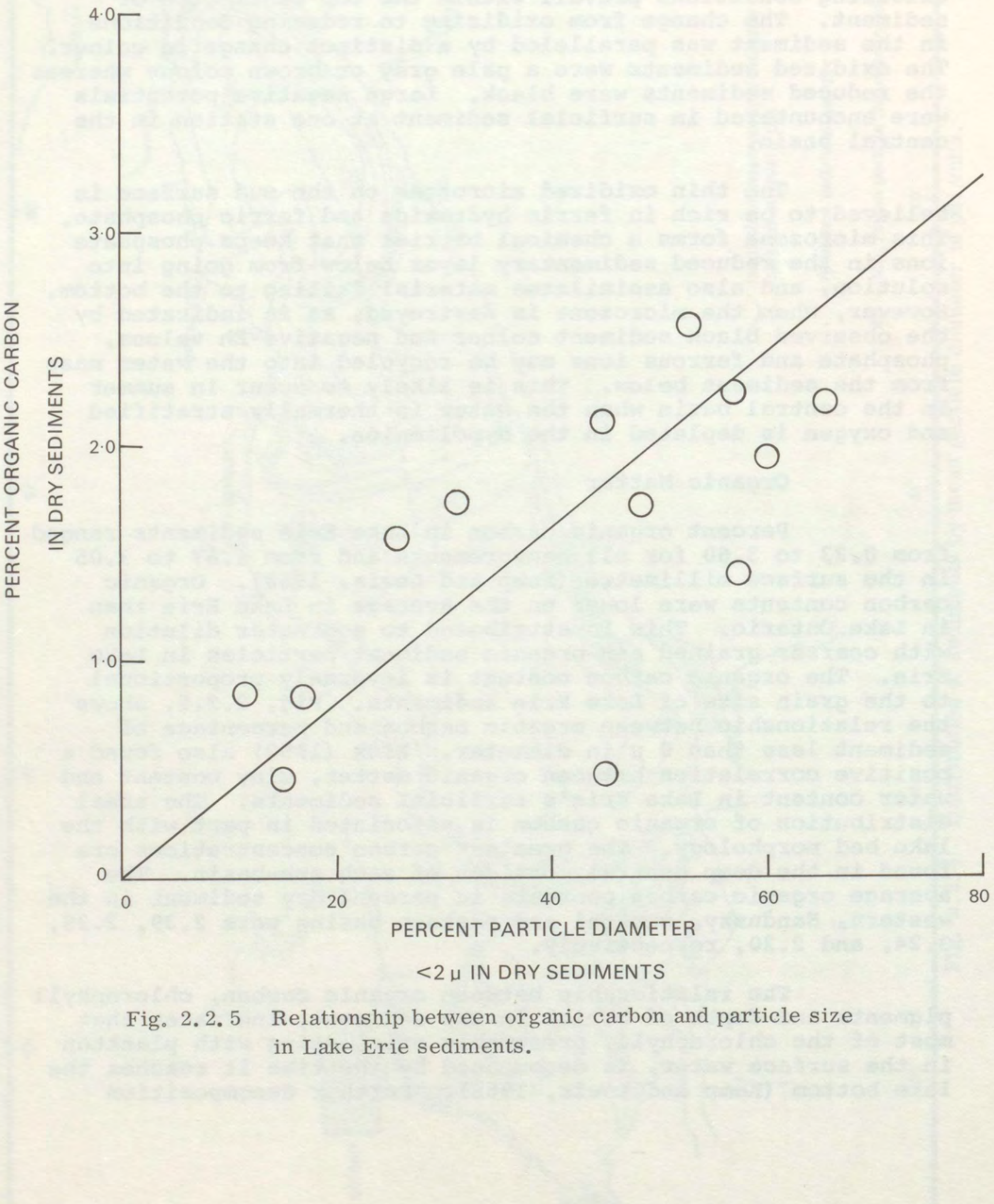


Fig. 2.2.5 Relationship between organic carbon and particle size in Lake Erie sediments.

within the sediment is shown by a rapid decrease in concentrations of organic carbon and chlorophyll degradation products with depth of burial. Approximately 34 percent of the organic matter and 74 percent of pheophytin pigments occurring in the surface sediment were decomposed at a depth of 2 inches. Thus the surficial muds are the locale of rapid alteration in the composition of the sediment organic fraction.

Other Chemical Parameters

Between July 28 and August 7, 1964, FWPCA sampled Lake Erie sediments at 60 locations and analyzed for total iron, total phosphorus, sulphide, ammonia nitrogen, nitrate and nitrite-nitrogen, organic nitrogen and chemical oxygen demand. The areal distribution of each parameter closely resembled that of organic carbon in which values are grouped around each sub-basin with the largest values occurring towards the basin centres. Most of these 1964 results are summarized together with the 1967-68 results in Section 3.1.4. Average sulphide contents for the western, Sandusky, central and eastern basins were 0.23, 0.15, 1.16 and 0.04 milligrams/gram (mg/g), respectively in 1964. Except for total iron and nitrogen, which seem to vary considerably with the time of sampling, most parameters decreased in average values from west to east, being highest in the western basin and lowest in the eastern basin. Sampling by the FWPCA again in 1967 showed similar values and patterns.

2.3 CHEMISTRY

2.3.1 Eutrophication

An acceleration in the rate of addition of plant nutrients to natural waters results in increased biological populations and production. This process, termed eutrophication, occurs both naturally and as a result of waste-disposal and agricultural practices. In the latter sense, man's nutrient pollution of the environment or cultural eutrophication is a special aspect of pollution dealing with those pollutants that lead to an overall increase in biological production.

Suspended algae in open water (phytoplankton), rooted plants, and attached algae on the bottom in shallow areas constitute the plant life of lakes. These plants, directly or indirectly, serve as the main source of food for all of the animals that make up the complex communities of life in lakes. Many factors control the biological productivity of lakes; however, since plant growth depends on the supply of essential nutrients, lakes well supplied with nutrients tend to be the most productive. Indeed, this relationship provides a recognized basis for lake classification.

According to the trophic system of lake classification, lakes are generally classified as *oligotrophic*, *mesotrophic* or *eutrophic*, depending on their degree of plant nutrient enrichment and biological productivity. Oligotrophic lakes are poorly supplied with plant nutrients and support little plant growth. As a result biological production is generally low, their waters are clear and the deep waters are well supplied with oxygen throughout the year. Populations of salmonid and coregonid fish are characteristic of the oxygen-saturated bottom waters of oligotrophic lakes. Eutrophic lakes are rich in plant nutrients and support a heavy growth of plants. As a result, biological production is generally high, the waters are turbid from the dense growth of phytoplankton, and the deep waters during periods of restricted circulation become deficient in oxygen as a result of the decomposition of great quantities of organic material produced. The low concentrations of dissolved oxygen in bottom waters during periods of restricted vertical circulation largely limit the fish fauna to warm-water species. In extreme cases of eutrophy, algae become so abundant as to cause offensive odours in bays, clog water intake lines, and generally reduce the water quality. Lakes become more eutrophic as their basins become filled with sediment. Lakes in regions of sedimentary rock drainage are more eutrophic in character than those in regions of igneous rock drainage. Lakes intermediate between oligotrophic and eutrophic, that is, with a moderate supply of nutrients, moderate plant abundance and biological production, are known as mesotrophic lakes.

If the supply of nutrients to an oligotrophic lake is progressively increased, the lake will become more mesotrophic in character; with further continuing enrichment it will eventually become eutrophic and finally extremely eutrophic. This whole process of progressively becoming more eutrophic is known as *eutrophication*. Thus, eutrophication refers to the whole complex of changes which accompany continuing enrichment by plant nutrients. These include progressive increases in the growth of algae and other plants, general increases in biological productivity, successive changes in the kinds of plants and animals living in the lake, oxygen depletion in deep water during periods of restricted circulation, and decreasing depth as a result of accumulating organic sediments. The three general lake types (oligotrophic, mesotrophic and eutrophic) are merely relative in that they indicate the general degree of eutrophy in a spectrum ranging from oligotrophy to eutrophy.

Sewage, some industrial wastes and surface runoff from heavily fertilized farmlands contain significant concentrations of essential plant nutrients which enrich lake waters. With increased urbanization, industrialization, intensified agricultural practices and use of phosphate-based detergents in recent decades, there has been an ever-increasing number of examples of such enrichment and rapid eutrophication of lakes in many parts of the world. Lakes of all types and sizes have been affected. In some cases even very oligotrophic lakes have become eutrophic in a matter of a few decades. The end result of excessive enrichment is always the same, production of dense nuisance growths of algae and aquatic weeds that generally degrade water quality and render the lake useless for many purposes. Heavy enrichment particularly favours the growth of certain algae that produce unpleasant side effects. *Cladophora*, an attached alga growing on rocky shores often accumulates on beaches when disrupted by wave action. Blue-green algae can also accumulate at the shore as a result of wind action causing unsightly, odourous scums.

The similarity of the eutrophication resulting from man's activities as described above to natural eutrophication is often over-emphasized. The natural enrichment and eutrophication of lakes are generally so slow that they can only be measured on a geological time scale. For example, most lakes in north temperate regions were created by glacial action six to twelve thousand years ago; yet many of these lakes are still in an oligotrophic condition. The extent of enrichment and eutrophication which has occurred in many of the world's lakes in the past few decades would require thousands of years under natural conditions. Indeed, such enrichment might never be possible naturally. It is unfortunate and misleading, that the drastic eutrophication in lakes affected by man is so often referred to as a mere acceleration of a natural phenomenon. This analogy often gives the impression that eutrophication is irreversible. That this is not true has been demonstrated in a number of cases where man's wastes have been diverted away from lakes and they have subsequently recovered to a less eutrophic condition.

Sewage effluents, certain industrial wastes and the runoff from agricultural land are all extremely rich in a number of plant nutrients. Of these nutrients, compounds of phosphorus and nitrogen are generally considered to be the most significant and their key role in eutrophication has long been recognized. Experience in many lakes has shown that of these two, phosphorus is most often the easier to control. Although many other nutrients and growth promoting substances are common in sewage effluents and other wastes, there is no evidence from the present state of knowledge for attributing a controlling role to any of these other substances in the eutrophication process. On the other hand, they may play a role in determining the composition of the biological community or the type of algal water bloom.

2.3.2 Nutrient Chemistry

Phosphorus

Phosphorus is an essential constituent of all living organisms. It occurs as a component of deoxyribonucleic acids (genes) which are involved in cellular reproduction. Ribonucleic acids play an essential role in protein synthesis and form various intermediary compounds involved in the transfer of energy in respiration and photosynthesis. With the exception of some recently discovered compounds containing C-P bonds and micro-organisms that are capable of reducing phosphate to phosphine, the element occurs naturally on the earth only in a fully oxidized state. The forms of the phosphorus compounds present in lake water are imperfectly known. Most analyses have been restricted to relatively simple assays for orthophosphate and total-phosphorus.

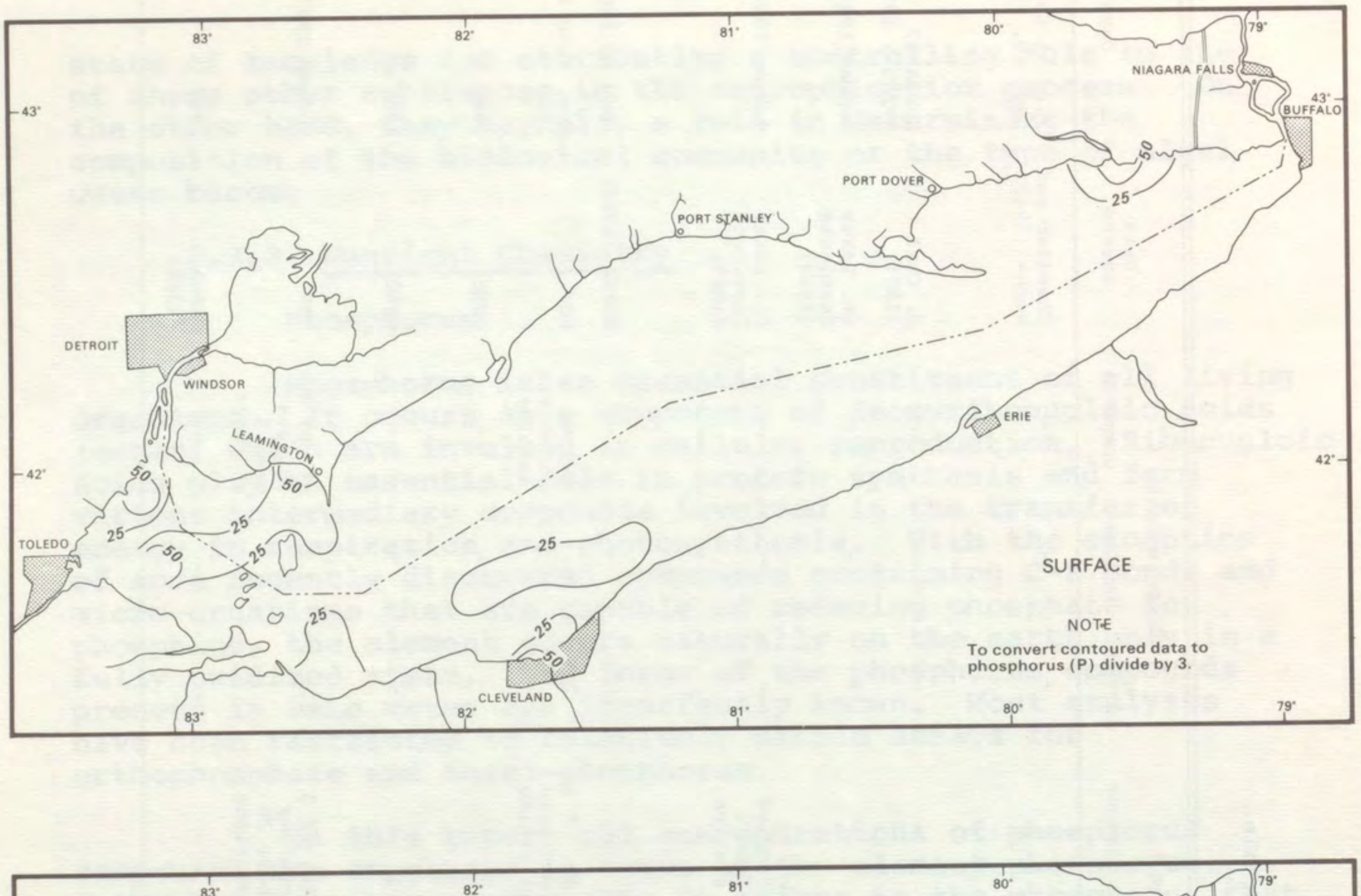
In this report all concentrations of phosphorus compounds are expressed in terms of the element phosphorus. Orthophosphate-phosphorus (PO_4-P) refers to the phosphorus that occurs as orthophosphate ions (such as H_2PO_4, HPO_4, PO_4, $NaHPO_4$, $CaHPO_4$) in a filtered sample of water; total-phosphorus (total-P) refers to the phosphorus present as orthophosphate ions after acid digestion of an unfiltered sample of lake water and includes both the inorganic orthophosphate and the phosphorus present in organic substances. The terms soluble phosphate-P and reactive phosphate-P are treated here as equivalents of orthophosphate-P.

Table 2.3.1 summarizes the information available on past and present concentrations of PO_4-P in the waters of Lake Erie. With reference to the recent years, 1963 to 1967, all data show that average summer concentrations of both PO_4-P and total-P in surface waters are highest in the western basin (17 to 40 μg PO_4-P/l), less in the central (5 to 20 μg PO_4-P/l) and least in the eastern basin (3 to 10 μg PO_4-P/l). Representative patterns for 1967 showing the distribution of PO_4-P values in the surface and bottom waters of Lake Erie are given in Fig. 2.3.1 and 2.3.2, respectively. In the relatively well-mixed waters of the western basin the concentrations of PO_4-P tend to be more uniform with depth than in the central and eastern basins. Particularly in the eastern basin, phosphorus is

Table 2.3.1 Average concentrations of orthophosphate (μg PO_4-P/l) in Lake Erie.

Shore zones U.S. W	U.S. C	U.S. E	Canada W	Canada C	Canada E	Western basin surface	Western basin bottom	Western basin comment	Central basin surface	Central basin bottom	Central basin comment	Eastern basin surface	Eastern basin bottom	Eastern basin comment	Data source	Date
-	-	-	-	-	-	3.9	-	Frequent determinations at Bass Is. region	-	-	-	-	-	-	Chandler and Weeks (1945)	July 31 to Dec. 10, 1942
-	-	-	-	-	-	4.6	-	Island area	-	-	-	-	-	-	H. Curl (1959)	April 27 May 31, 1951
-	-	-	-	-	-	65	-	Single determination	-	-	-	-	-	-	Gt. Lakes Institute (1964)	Summer 1962
-	-	-	-	-	-	28	-	Av. of 3 determinations at 1 mid-basin station	30	-	Samples from 1 station	-	-	-	Gt. Lakes Institute (1965)	Summer 1963
-	-	-	-	-	-	30*	-	-	10*	-	-	10*	-	-	FWPCA (1968)	1963 to 1964
-	-	-	-	-	-	-	-	-	4.6	11.1	Av. of 11 stations 1 cruise	2.6	22.8	Av. of 3 mid-basin samples	NHW	Aug. 8 to 14, 1966
15 to 100	-	-	15 to 30	5 to 15	5 to 25	-	-	-	-	-	-	-	-	-	OWRC	1966
20 to 100	-	-	15 to 30	10 to 15	10 to 15	-	-	-	-	-	-	-	-	-	OWRC	1967
-	-	-	-	-	-	17	18	Av. of 3 summer cruises	4.6	6.5	Av. of 3 cruises over 20 stations	2.9	7.2	Av. of 3 cruises over 8 stations	EMR	Summer 1967
-	-	-	-	-	-	40*	-	-	20*	-	-	10*	-	-	FWPCA (1968)	1967

* Represents averaged data from three depths (surface, middle, bottom)
\- No data



2.3.1, 2.3.2 Distribution of orthophosphate ($\mu g\ PO_4/1$) in surface and bottom waters, summer of 1967.

released from the sediments during periods of restricted vertical circulation. The concentrations of both PO_4-P and total-P tend to be highest in late winter and early spring (Chandler and Weeks, 1945), conforming to the usual pattern observed in most north temperate lakes. This is a result of reduced biological activity in winter. Data for total-P in the three basins of Lake Erie are given in Table 2.3.2. The ratio of total-P to PO_4-P has been reported as ranging from 1:1 (Federal Water Pollution Control Administration, 1968b) to 3:1 (Chandler and Weeks, 1945).

It is clear from detailed information in the studies cited in Tables 2.3.1 and 2.3.2 that locally high concentrations of PO_4-P and total-P are observed adjacent to major centres of population, industry and agriculture, or rivers draining such regions (Section 3.2). This is true, for example, of the densely settled area draining into the western basin, and for localized areas adjacent to Metropolitan Detroit, Toledo and Cleveland on the United States side, and Kingsville and Leamington on the Canadian side. Measurements by OWRC and the FWPCA show that PO_4-P concentrations at the mouth of the Detroit River are higher on the United States side than on the Canadian side. This suggests that while there may be some transboundary movement, the main masses of phosphorus-containing pollutants remain on the same side of the mid-channel flow that they entered.

Neither direct estimates are available on the rate of removal of phosphorus compounds from Lake Erie by sedimentation, on the rate of release of phosphates from the sediments, nor on the rates at which phosphorus compounds are recycled from bacteria and zooplankton to algae in the upper illuminated layers. Curl (1959) however, has noted a direct statistical relationship between turbidity and PO_4-P in the western basin of Lake Erie.

A comparison of early data on Lake Erie with the most recent information available (Table 2.3.1) suggests that the concentration of PO_4-P in the western basin of Lake Erie increased approximately four to ten times between the periods 1942-1951 and 1963-1967. Because of the lack of data for the central and eastern basins prior to 1963, no comparable estimates are available for the rest of the lake.

Nitrogen

Nitrogen, like phosphorus, is an essential constituent of all living organisms. It occurs as a component of all major classes of biochemical compounds and plays a unique role in the structure of proteins and enzymes. Nitrogen is present in

Table 2.3.2 Average concentrations of total-phosphorus (μg P/l) in Lake Erie.

Shore zones U.S. W	C	E	Canada W	C	E	Western basin surface	bottom	comment	Central basin surface	bottom	comment	Eastern basin surface	bottom	comment	Data source	Date
-	-	-	-	-	-	14.4	-	Frequent determinations at Bass Is. region	-	-	-	-	-	-	Chandler and Weeks (1945)	July 31 to Dec. 10, 1942
-	-	-	-	-	-	33	-	Bass Is. region	-	-	-	-	-	-	Beeton (1961)	1958
-	-	-	-	-	-	36	-	Bass Is. region	-	-	-	-	-	-	Beeton (1961)	1959
-	-	-	-	-	-	20	-	Single determination	-	-	-	-	-	-	Gt. Lakes Institute (1964)	Summer 1962
-	-	-	-	-	-	36	-	Av. of 3 determinations at one mid-basin station	-	-	-	-	-	-	Gt. Lakes Institute (1965)	Summer 1963
50 to 400	-	20 to 60	40 to 70	20 to 40	20 to 30	-	-	-	-	-	-	-	-	-	OWRC	1966
40 to 190	-	20 to 70	30 to 60	20 to 30	20 to 30	-	-	-	-	-	-	-	-	-	OWRC	1967
-	-	-	-	-	-	60*	-	-	20*	-	-	20*	-	-	FWPCA (1968)	1967

* Represents averaged data from three depths (surface, middle, bottom)
\- No data

organisms and lake waters in various oxidation states ranging from -3 (ammonia and amino groups) to +5 (nitrate). Most lake water analyses have been restricted to ammonia (NH_3), nitrite (NO_2), nitrate (NO_3), and Kjeldahl-N (NH_3-N plus organic-N). Total-N in this report refers to the sum of NO_2-N, NO_3-N and Kjeldahl-N. Kjeldahl-N was determined on unfiltered samples. All data are presented in terms of the element N.

Studies of the distribution of NO_3-N in the waters of Lake Erie are summarized in Table 2.3.3. Comparable information of NH_3-N is summarized in Table 2.3.4; and for total-N and NO_2-N in Table 2.3.5. In addition, representative lake-wide patterns of NO_3-N during the summer are given in Fig. 2.3.3 and 2.3.4 for surface and bottom waters, respectively.

With reference to the present distribution and abundance of nitrogen compounds all surveys have shown that concentrations are much higher in the western basin than in the central and eastern basins. The data of the FWPCA (1968a, 1968b), for example, indicate average concentrations based on three representative depths during the ice-free season to be approximately 120-160 µg NH_3-N/l, 120-200 µg NO_3-N/l and 360-370 µg organic-N/l in the western basin as compared to 86-90 µg NH_3-N/l, 60-90 µg NO_3-N/l and 240-340 µg organic-N/l in the central and eastern basins. Unpublished data from NHW and EMR for surface waters during the summer show lower nitrate values for the lake as a whole than those reported by the FWPCA (1968a, 1968b), and much lower values for the eastern basin than for the central basin. Nearshore concentrations of nitrogen compounds in the western basin, particularly in the vicinity of harbours and urban centres, are more than twice as high as in offshore areas; whereas in the central and eastern basins they average only slightly higher (Federal Water Pollution Control Administration, 1968a, 1968b).

Concentrations of nitrate show pronounced monthly fluctuations (Fig. 2.3.5 and 2.3.6). There is a late summer minimum in surface water (probably associated with biological uptake) and a winter and spring maximum during times of low biological activity.

The vertical distribution of nitrate in the western basin is fairly uniform (Chandler and Weeks, 1945; Wright, 1955; Beeton 1961; Federal Water Pollution Control Administration, 1968a, 1968b). Curl (1959) however, did find evidence of stratification in the Bass Island region in November of 1950. He attributed this to nutrient-rich Maumee River water flowing under the main water mass from the Detroit River. As shown in Fig. 2.3.7 there is an increase in nitrate concentration in the

Table 2.3.3 Average concentrations of nitrate-nitrogen ($\mu g\ NO_3\text{-}N/l$) in Lake Erie.

Shore zones U.S. W	U.S. C	U.S. E	Canada W	Canada C	Canada E	Western basin surface	Western basin bottom	Western basin comment	Central basin surface	Central basin bottom	Central basin comment	Eastern basin surface	Eastern basin bottom	Eastern basin comment	Data source	Date
-	-	-	-	-	-	-	-	-	85	-	Erie, Pennsylvania	-	-	-	Lewis (1906)	1901 to 1903
-	-	-	-	-	-	-	-	-	-	-	-	116	-	-	Fish (1960)	Aug. 28 to Sept. 14, 1928
-	-	-	-	-	-	100	-	Av. over 10 stations	-	-	-	-	-	-	Wright (1955)	July to Sept. 1930
-	-	-	-	-	-	123	-	Frequent determinations at Bass Is. region	-	-	-	-	-	-	Chandler and Weeks (1945)	June 18 to Sept. 30, 1942
-	-	-	-	-	-	-	-	-	400	-	Erie, Pennsylvania, Bureau of Water (1956)	-	-	-	-	1956
-	-	-	-	-	-	-	-	-	300	-	Erie, Pennsylvania, Bureau of Water (1958)	-	-	-	-	1958
-	-	-	-	-	-	120*	-	-	90*	-	-	90*	-	-	FWPCA (1968)	1963 to 1964
-	-	-	-	-	-	-	-	-	9	30	Av. of 1 cruise over 51 offshore stations	3	46	1 cruise over 24 offshore stations	NHW	Aug. 8 to 14, 1966
-	-	-	-	-	-	76	81	Av. of 5 cruises over 15 offshore stations	33	64	Av. for 5 cruises over 36 offshore stations	8	65	Av. for 5 cruises over 18 offshore stations	EMR	June to Sept. 1967
20 to 100	-	30 to 50	80 to 100	20 to 50	10 to 30	-	-	-	-	-	-	-	-	-	OWRC	1967
-	-	-	-	-	-	200*	-	-	50*	-	-	60*	-	-	FWPCA (1968)	1967

* Represents averaged data from three depths (surface, middle, bottom)
\- No data

Table 2.3.4 Concentrations of ammonia-nitrogen (μg NH_3-N/l) in Lake Erie.

Shore zones U.S. W	Shore zones U.S. C	Shore zones U.S. E	Shore zones Canada W	Shore zones Canada C	Shore zones Canada E	Western basin surface	Western basin bottom	Western basin comment	Central basin surface	Central basin bottom	Central basin comment	Eastern basin surface	Eastern basin bottom	Eastern basin comment	Data source	Date
-	-	-	-	-	-	-	-	-	46	-	-	-	-	-	Lewis (1906)	1901 to 1903
-	-	-	-	-	-	-	-	-	50	-	-	-	-	-	Beeton (1961)	1925
-	-	-	-	-	-	13	-	-	-	-	-	-	-	-	Wright (1955)	July to Sept. 1930
-	-	-	-	-	-	36	-	-	-	-	-	-	-	-	Chandler and Weeks (1945)	June 18 to Sept. 30, 1942
-	-	-	-	-	-	33	-	-	-	-	-	-	-	-	International Joint Commission (1951)	1946 to 1948
-	-	-	-	-	-	-	-	-	30-45	-	Erie, Pennsylvania	-	-	-	Beeton (1961)	1956 to 1958
-	-	-	-	-	-	160*	-	-	90*	-	-	90*	-	-	FWPCA (1968)	1963 to 1964
50 to 100	-	20 to 70	40 to 80	30 to 50	20 to 50	-	-	-	-	-	-	-	-	-	OWRC	1967
-	-	-	-	-	-	170*	-	-	100*	-	-	70*	-	-	FWPCA	1967

* Represents averaged data from three depths (surface, middle, bottom)
- No data

Table 2.3.5 Concentrations of total nitrogen (µg N/l) and nitrite-nitrogen (µg NO_2-N/l) in Lake Erie.

Shore zones U.S. W	U.S. C	U.S. E	Canada W	Canada C	Canada E	Western basin surface	Western basin bottom	Western basin comment	Central basin surface	Central basin bottom	Central basin comment	Eastern basin surface	Eastern basin bottom	Eastern basin comment	Data source	Date
Total Nitrogen																
-	-	-	-	-	-	265	-	-	-	-	-	-	-	-	Chandler & Weeks (1945)	June 18 to Sept. 30, 1942
-	-	-	-	-	-	830	-	Island area	-	-	-	-	-	-	Beeton (1961)	1958
-	-	-	-	-	-	710*	-	1	430*	-	3	420	-	-	FWPCA (1968)	1963 to 1964
4000	-	-	-	-	-	740*	-	2	470*	-	4	470	-	-	FWPCA (1968)	1967
Nitrite-Nitrogen																
-	-	-	-	-	-	8	-	-	-	-	-	-	-	-	Chandler & Weeks (1945)	June 18 to Sept. 30, 1942
-	-	-	-	-	-	5	-	-	-	-	-	-	-	-	Wright (1955)	July to Sept. 1930
10 to 60	-	2 to 4	10	3 to 12	3 to 8	-	-	-	-	-	-	-	-	-	OWRC	1967

* Represents averaged data from three depths (surface, middle, bottom)
- No data

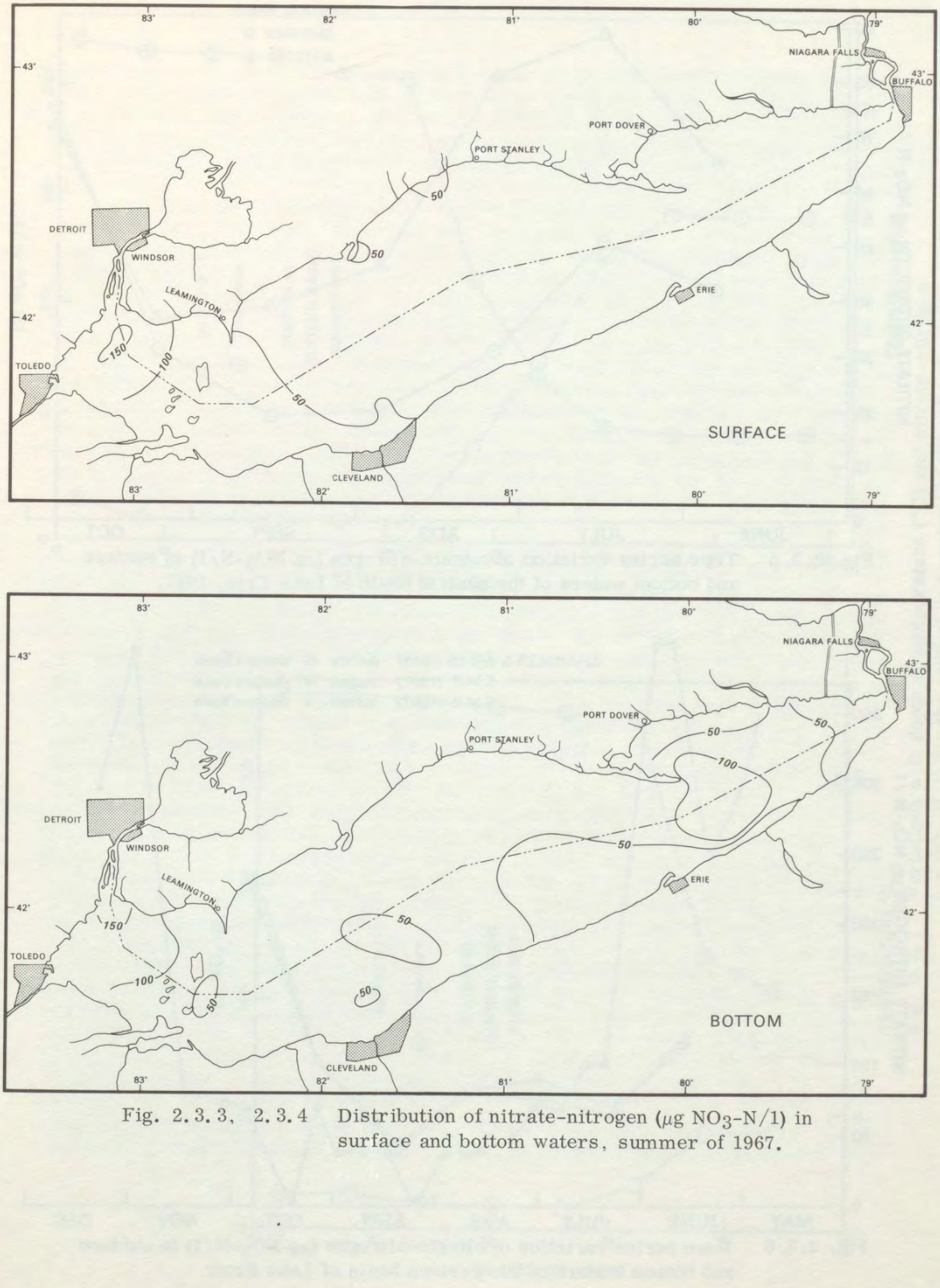


Fig. 2.3.3, 2.3.4 Distribution of nitrate-nitrogen (μg NO_3-N/1) in surface and bottom waters, summer of 1967.

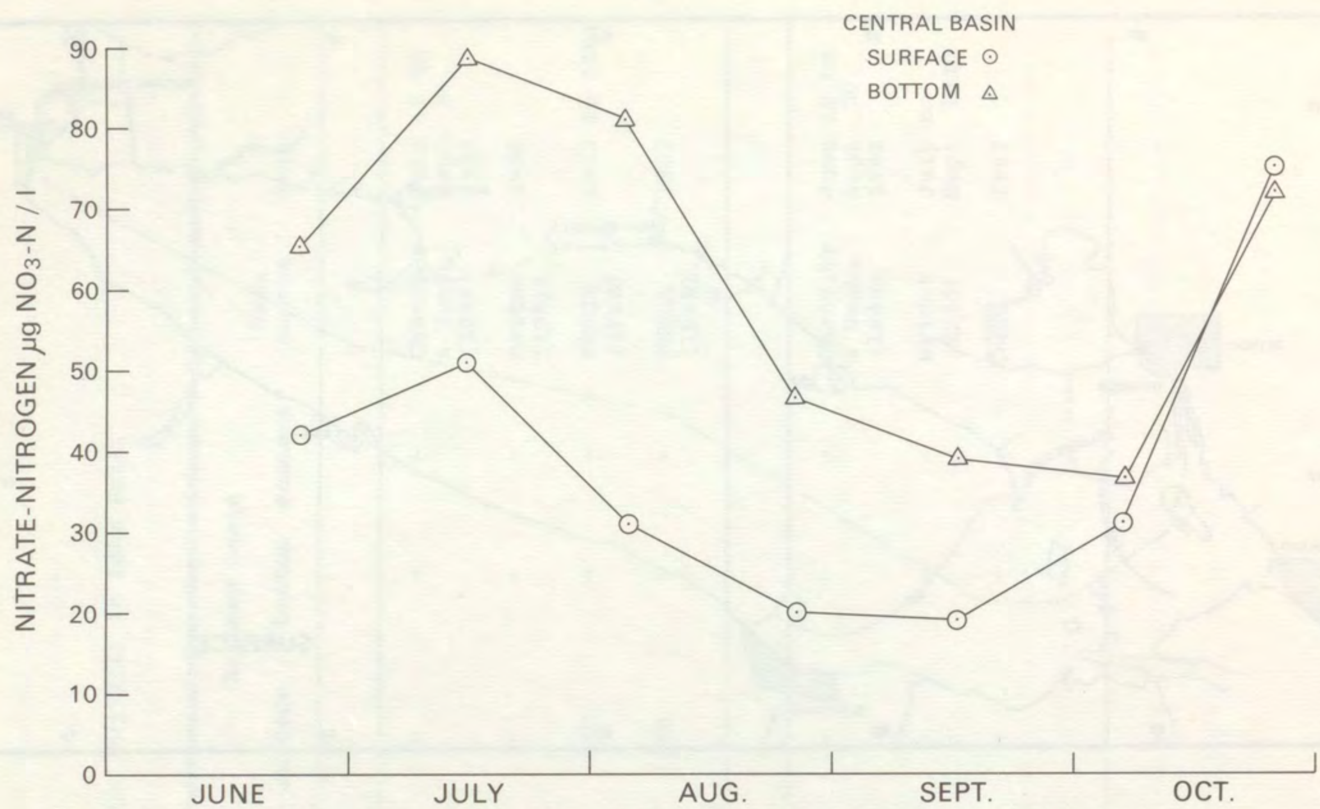


Fig. 2.3.5 Time series variation of nitrate-nitrogen (μg NO_3-N/1) in surface and bottom waters of the central basin of Lake Erie, 1967.

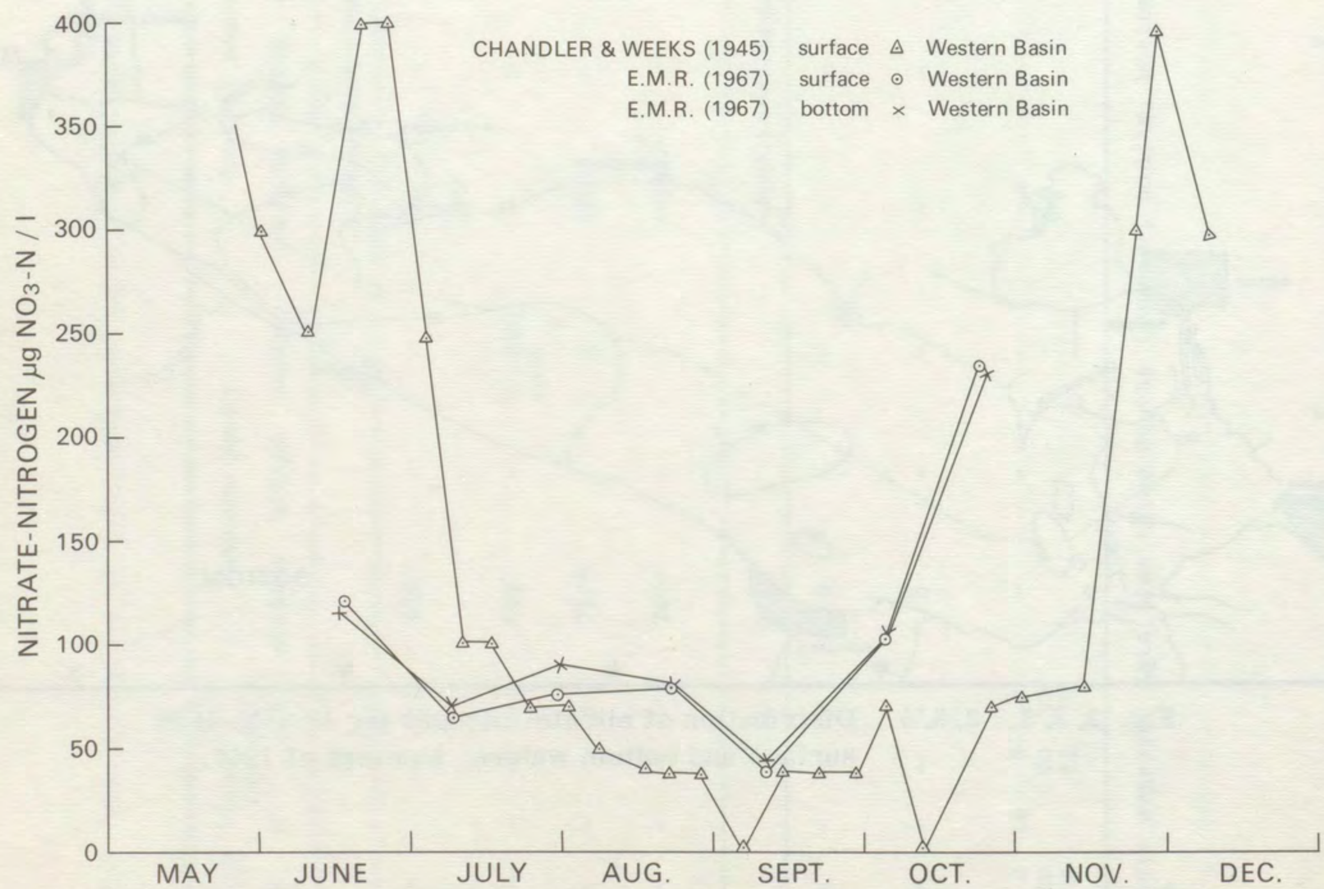
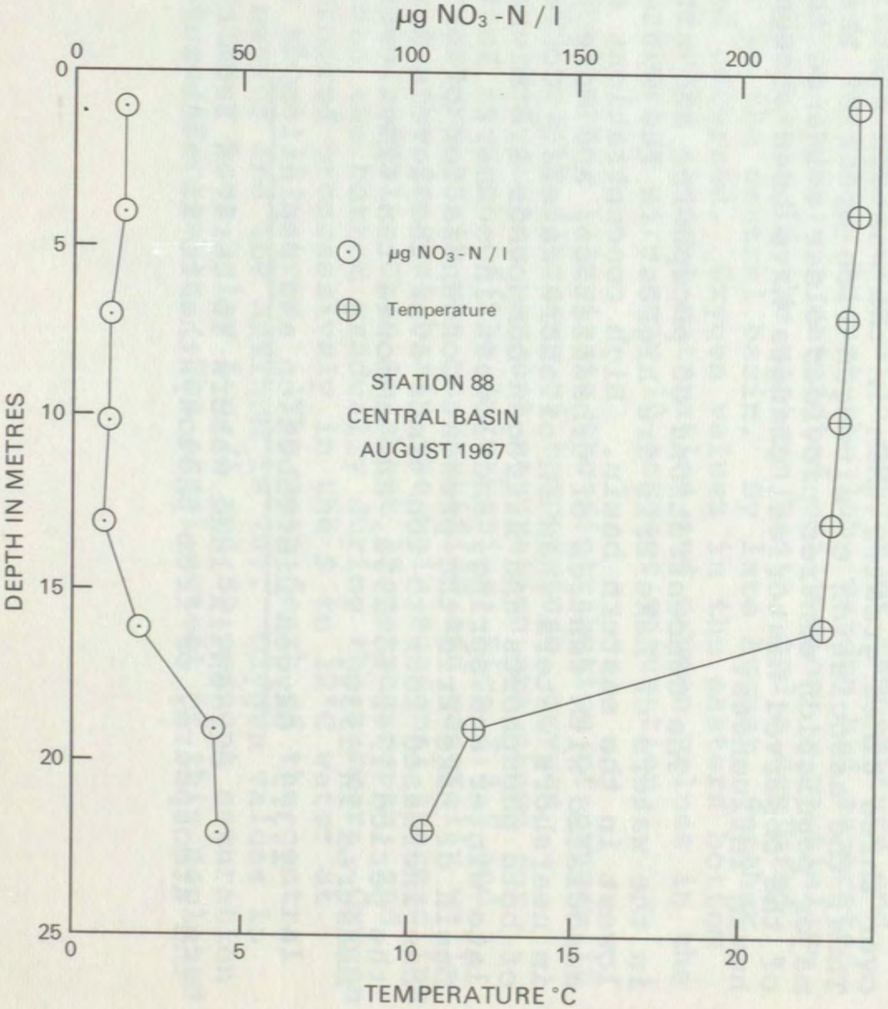


Fig. 2.3.6 Time series variation of nitrate-nitrogen (μg NO_3-N/1) in surface and bottom waters of the western basin of Lake Erie.



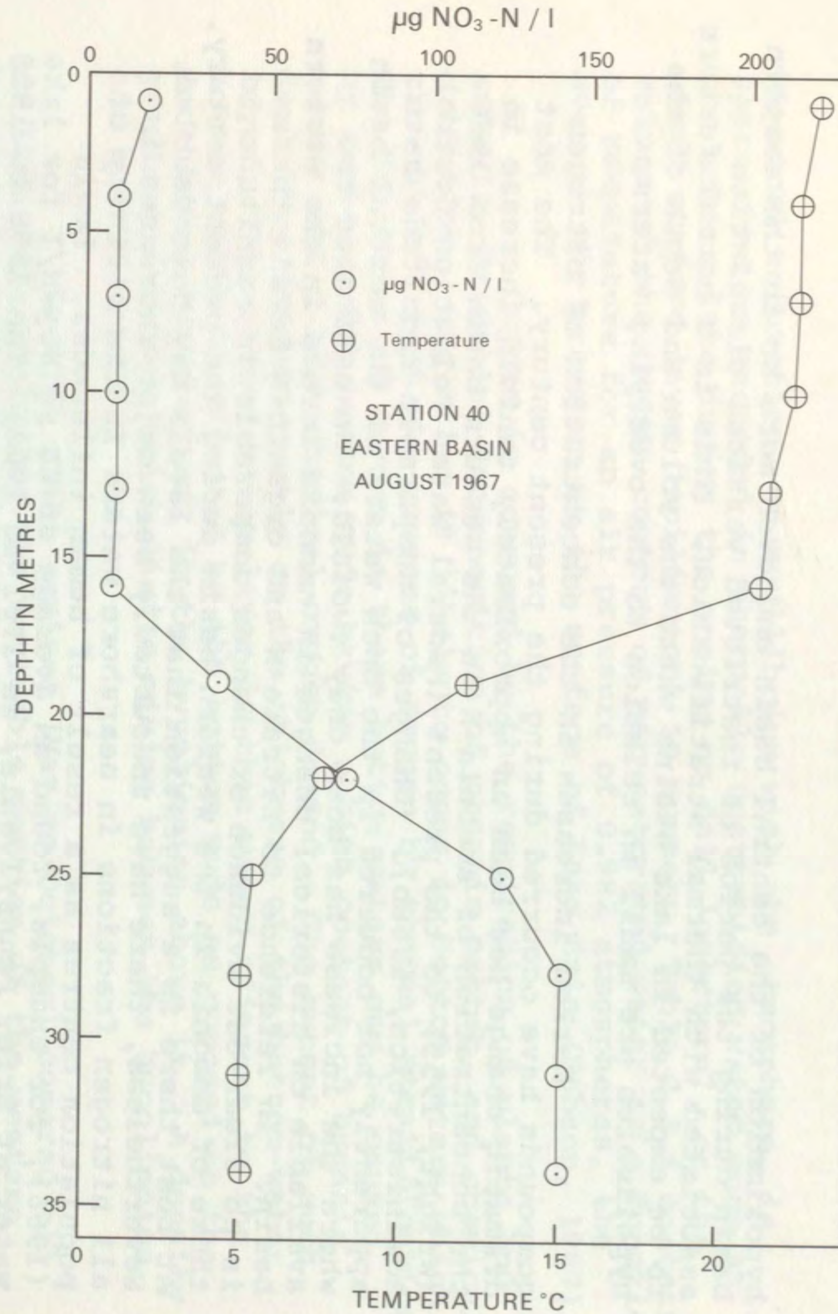


Fig. 2.3.7 Variations with depth of temperature (°C) and nitrate-nitrogen (μg NO_3-N/1) for the central and eastern basins of Lake Erie, 1967.

hypolimnion of the central basin and even more so in the eastern basin during the period of restricted vertical circulation associated with thermal stratification. This is a normal feature to be expected in lake basins where the volume and depth of the hypolimnion are small in relation to the overlying waters.

Marked increases in the concentration of nitrogen compounds have occurred during the present century. The most dramatic change has been an approximately tenfold increase in the concentration of ammonia-N in the western basin from 1930 (Wright, 1955) to the present (Federal Water Pollution Control Administration, 1968b). Changes of comparable magnitude have apparently not occurred in the open waters of the central basin where the increase has been only twofold. No estimates are available on historical changes in ammonia levels in the eastern basin. In reference to nitrate-N and organic-N levels there is no clear-cut evidence of changes comparable in magnitude to those of ammonia in the western basin during the present century. At best there is a suggestion that the levels may have doubled. Nevertheless, there have undoubtedly been major increases in all nitrogen fractions in nearshore waters in the vicinity of population centres as a result of human influences. Lewis (1906), for example, found an average of 85 μg NO_3-N/l for lake water at Erie, Pennsylvania, in 1901 to 1903. The 1956 to 1958 concentrations recorded by the Bureau of Water at Erie were several times this value, 300 to 400 μg NO_3-N/l. Also, lake water offshore from the mouth of the Maumee River has total-N values over three times greater than in the western basin as a whole. Thus, the association of nitrogen-rich areas of the lake with major population centres provides clear evidence that the bulk of the observed historical changes have been brought about by human influences.

The concentrations of phosphorus and nitrogen compounds in the waters of Lake Erie are highest in the western basin and lowest in the eastern basin. High concentrations are generally associated with centres of urbanization, and more pronounced in nearshore waters than in offshore waters. Concentrations of both phosphorus and nitrogen compounds are highest during late winter and spring, and lowest in summer. In the western basin of Lake Erie the present concentration of orthophosphate has increased four to ten times over the levels measured during the period 1942 to 1951, and ammonia ten times over the levels measured in 1930.

2.3.3 Oxygen Distribution and Depletion

Oxygen in lake waters is derived from contact with the atmosphere, or from photosynthesis in near-surface layers.

Physical saturation, or equilibrium with the atmosphere, is approached or exceeded in thermally unstratified water such as the entire lake during the spring or fall 'overturn', or the mixed surface layer (epilimnion) in summer. Table 2.3.6 contains values of the oxygen content of air-saturated water as a function of temperature for an air pressure of 0.982 atmospheres, the average air pressure at the surface of Lake Erie (Dobson, 1967).

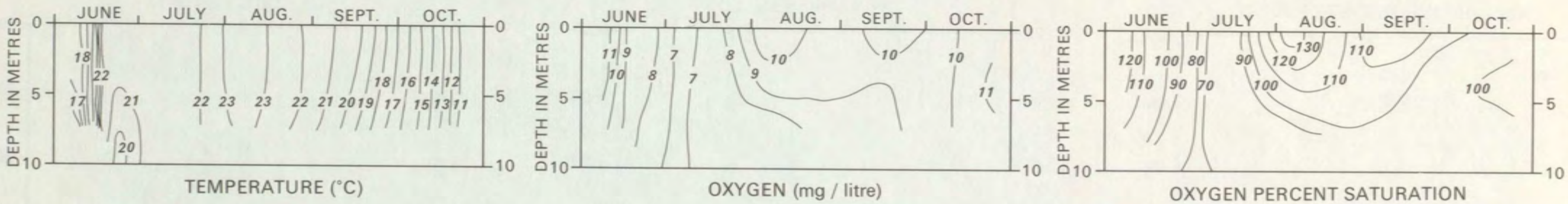
Oxygen is consumed by the respiration of plants and animals, bacterial decomposition of organic matter, and chemical oxidation. Depletion is likely to occur in bottom waters which are cut off from the sources of oxygen by thermal stratification. The depletion of oxygen in these bottom waters may be caused by contact with bottom muds having a high content of organic matter and a high chemical oxygen demand. The extent of such depletion depends partly on the thickness of the bottom-water layer. The bottom water layer is that water adjacent to the bottom which is affected by the bottom muds as opposed to the more homogeneous waters in the hypolimnion above it. A density gradient develops which limits mixing between the hypolimnion and bottom waters.

In 1967 eight cruises (May to October) covered all of Lake Erie including the navigable portion of the western basin. In early June the lake oxygen values ranged from 7 to 15 mg/l and 75 to 160 percent saturation. Much of the lake was supersaturated. Two or more distinct water types were not present, although there were wide ranges of temperature and oxygen values. By early August the lake waters had separated into three water types: a saturated epilimnion; a partially-depleted bottom water in the eastern basin, and a depleted bottom water in the central basin. By late August, further depletion had occurred. Oxygen values in the eastern bottom water were near 75 percent saturation and oxygen values in the central bottom water were near 10 percent saturation.

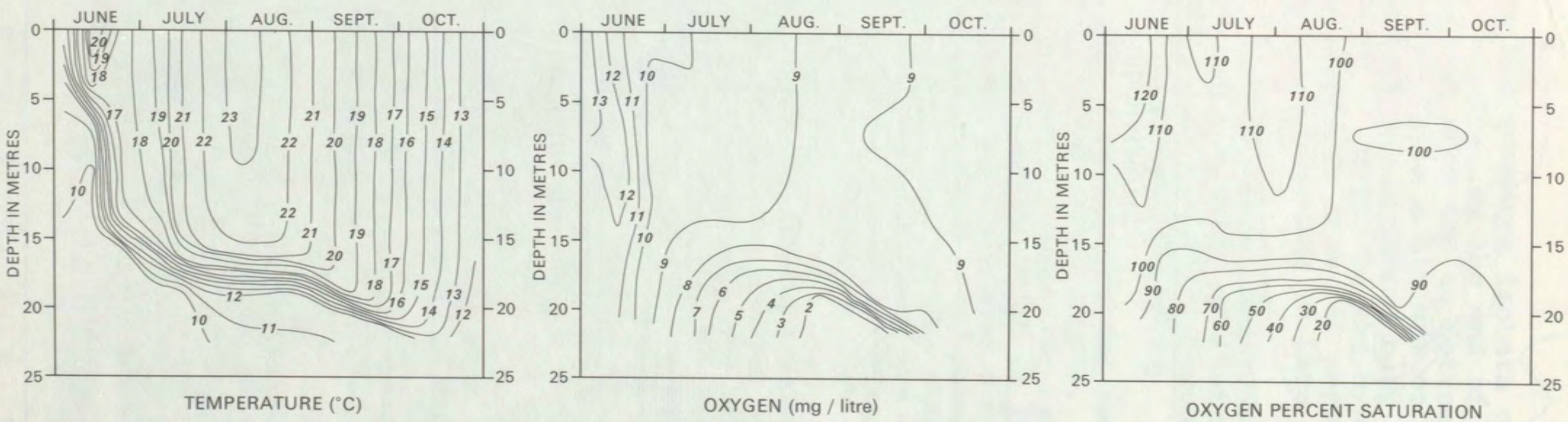
To further illustrate the distribution of oxygen in Lake Erie, time-depth diagrams of temperature, oxygen concentration, and oxygen percent saturation are shown for single stations in each of the lake basins, Fig. 2.3.8 and 2.3.9. The western basin was unstratified and generally well-oxygenated. In the central basin the main seasonal thermocline descended rapidly during June to about 15 metres depth, and then approached the bottom gradually during the summer. Oxygen depletion occurred progressively in the 9 to 12°C water at depths below about 18 metres. (The mean depth of the central basin is 19 metres and the maximum is 26). Oxygen values in the depleted layer were below 5 mg/l and 50 percent saturation during August and September. The areal extent of this depleted

Table 2.3.6 Oxygen solubility for air saturated water at 0.982 atm.

Temperature (°C)	Oxygen (mg/l)	Temperature (°C)	Oxygen (mg/l)
0	14.38		
1	13.97	16	9.69
2	13.59	17	9.49
3	13.22	18	9.29
4	12.85	19	9.10
5	12.52	20	8.93
6	12.20	21	8.75
7	11.89	22	8.58
8	11.60	23	8.42
9	11.32	24	8.26
10	11.06	25	8.11
11	10.81	26	7.96
12	10.57	27	7.83
13	10.34	28	7.69
14	10.11	29	7.55
15	9.90	30	7.42



LAKE ERIE 1967 - WESTERN BASIN
STATION 168
(Fig. 2.1.8)



LAKE ERIE 1967 - CENTRAL BASIN
STATION 88
(Fig. 2.1.8)

Fig. 2.3.8 Changes with time and depth of temperature, oxygen and percent saturation of oxygen for the western and central basins of Lake Erie, 1967.

LAKE ERIE 1967 EASTERN BASIN

STATION 39

(Fig. 2.1.8)

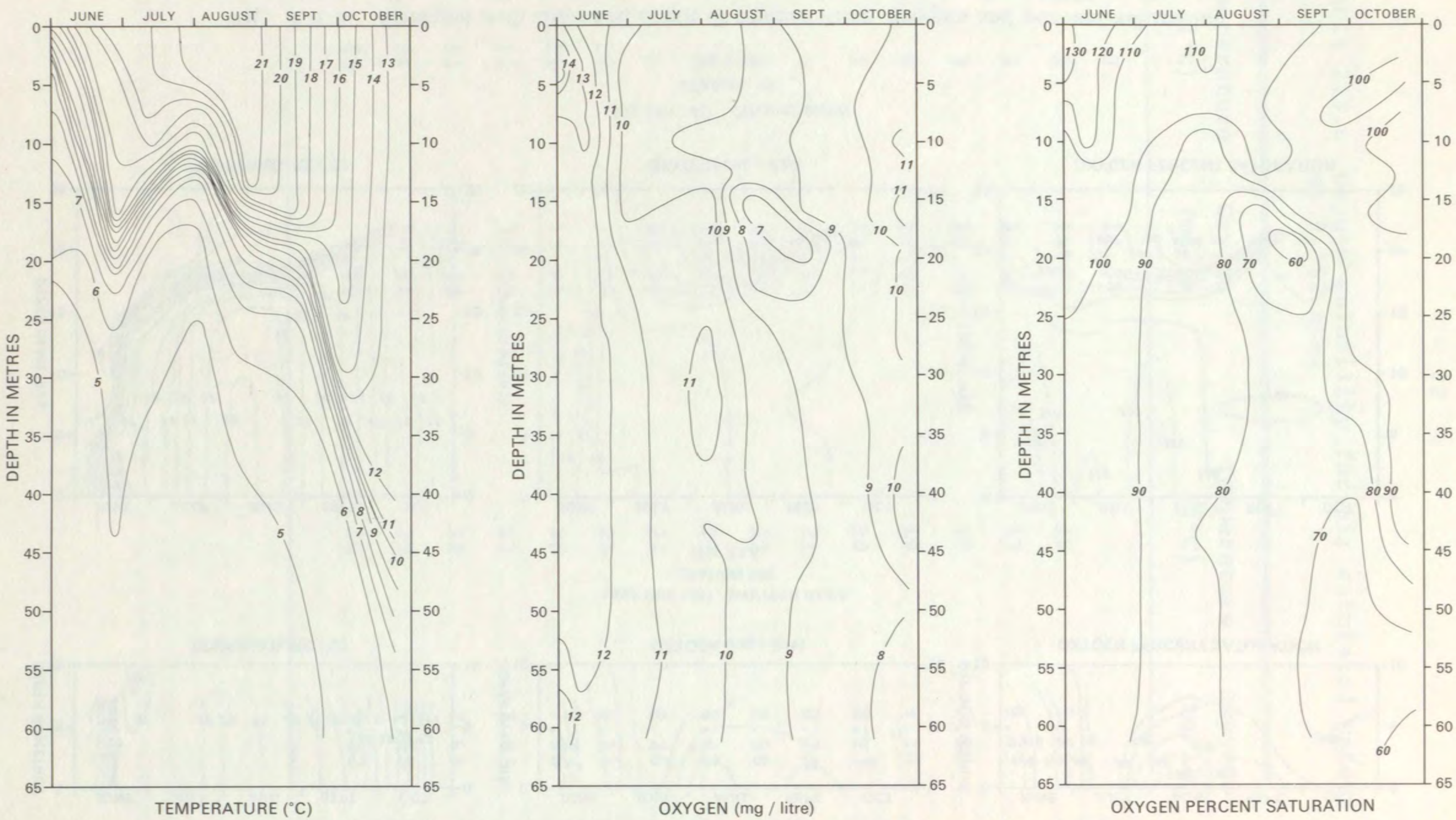


Fig. 2.3.9 Changes with time and depth of temperature, oxygen and percent saturation of oxygen for the eastern basin of Lake Erie, 1967.

layer is approximated by the 20-metre isobath on the chart of bottom topography (Fig. 1.1.1). By the end of September the central basin was well-mixed from top to bottom and again well-oxygenated. In the eastern basin a minimum of 6 mg/l dissolved oxygen and 60 percent saturation occurred near 19 metres depth during August and September. Oxygen in the hypolimnion of the eastern basin decreased gradually from 100 percent saturation in early June to 60 percent saturation in late October.

Carr (1962) reviewed oxygen observations up to 1961. It was cautiously stated, on the basis of limited data, that oxygen depletion in the central basin had become more extensive in comparison to the previous three decades.

A survey of oxygen in eastern and central Lake Erie was carried out in 1928 and 1929 (Fish, 1960). The bottom water of the central basin was only sparsely sampled. Nine of the central basin samples for August 16 to 18 had temperatures lower than 16.5°C. Oxygen values for these nine samples ranged from 4.4 to 8.3 mg/l, and 43 to 83 percent saturation. From these few observations in 1929 it cannot be stated with assurance that oxygen depletion in the central basin has changed markedly in the intervening years. It is suspected that the areal extent of depletion is much greater today than it was in 1929.

Oxygen depletion in the bottom waters of the central basin during August or September was reported by Beeton (1963) for the years 1959 and 1960, by Anderson and Rodgers (1964) for 1960, and by the United States Public Health Service (1965) for 1964. In the results reported by Beeton for September 4 and 5, 1959, the western two-thirds of the central basin had bottom water values below 2 mg/l dissolved oxygen, while values below 0.5 mg/l occurred in the southwest corner of the basin. Beeton's survey of August 30 to 31, 1960, and also a survey by the USPHS on August 14 to 31, 1964, revealed an area of depleted bottom water in the central basin with values of 0 to 2 mg/l dissolved oxygen with an areal extent approximating that of the 15-metre bottom contour (Fig. 1.1.1). The results of Anderson and Rodgers (1964) in their cruise of September 26 to 30, 1960 revealed a remnant of the oxygen-poor layer in the southeast half of the central basin, with values less than 10 percent saturation or 1 mg/l dissolved oxygen.

Britt (1955a) observed thermal stratification and partial depletion of oxygen near the bottom in the western basin during September, 1953, after a period of hot, calm weather. A similar occurrence was observed by Carr, Applegate and Keller (1965) in June, 1963. (Thermal stratification and oxygen depletion in the shallow western basin are usually prevented by the stirring effect of the wind).

Potos (1968) reported that taste and odour problems, occur in the Cleveland water supply in summer, during periods of southerly winds and upwelling of the oxygen-depleted bottom waters. He further stated this problem could be minimized by raising water intakes located in the hypolimnion into the epilimnion.

Dissolved oxygen loss in bottom waters of the western basin probably occurs in some local areas, perhaps as often as six times per season under certain types of weather conditions. Loss may also occur in winter in the western basin under ice cover. The FWPCA showed an average of 85 percent saturation in January 1968 in the western basin after about two weeks of total ice cover.

2.3.4 Major Ions and Trace Elements

Beeton (1965) has collected the available data for all of the Great Lakes and presented in graphical form the yearly concentration averages of sodium plus potassium, chloride, calcium, sulphate and total dissolved solids. Some of these graphs are reproduced in Fig. 2.3.10. The changes in concentration of these elements were small until about 1910. Since that time Lakes Erie and Ontario have shown the highest rates of increase, as well as the highest concentrations, followed by Lake Michigan and Lake Huron, whereas Lake Superior is evidently unaffected. Since the concentration of magnesium, most of which comes from limestones in the Lake Michigan basin, has not changed, the increase for the other ions most likely is due to the great increase in the population around Lakes Ontario, Erie, and Michigan.

The source of data includes isolated samplings and water-intake data to extensive lake-wide sampling. This no doubt gives rise to the rather wide scatter of points on Beeton's graphs, although the basic trends are clear. Based on his data, Table 2.3.7 gives the approximate average rate of increase of concentration (mg/l/decade) during the period 1910 to 1960 for the various lakes.

There are very few investigations in which a network of stations has been used to measure the concentrations of major ions in the lake. Fish (1960) determined chloride in 1928 and 1929, and Kramer (1961) measured calcium, magnesium, sodium, potassium, chloride and sulphate in July and October of 1960. More recently extensive surveys of chloride distribution in the central and eastern basins were undertaken in August 1966 by NHW and EMR and from 1966 to 1968 by OWRC.

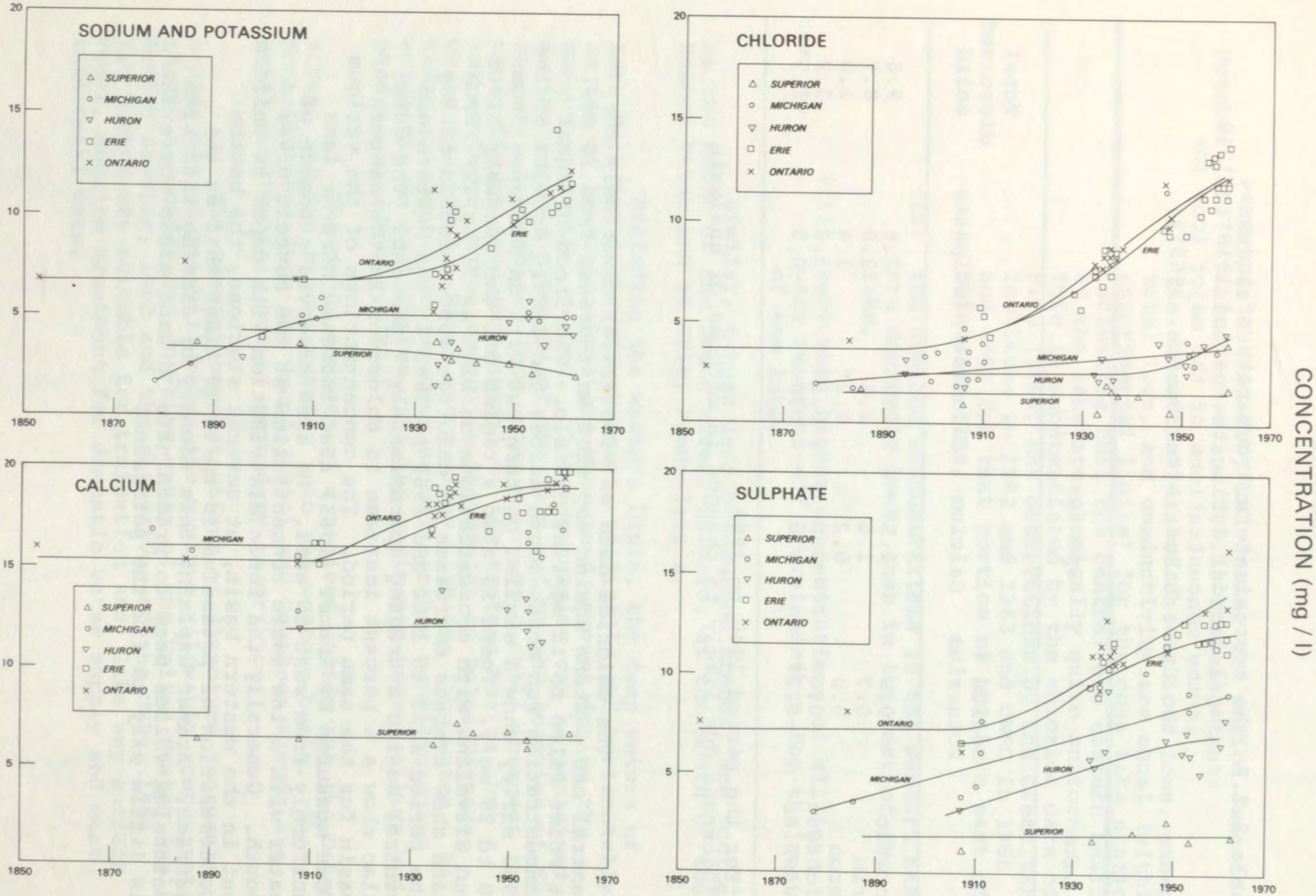


Fig. 2.3.10 Changes in the chemical characteristics of Great Lakes waters (After Beeton, 1965).

Table 2.3.7 The approximate average rate of increase (mg/l/decade) during the period 1910 to 1960 in the concentrations of the major ions for the Great Lakes (After Beeton, 1965).

Lake	Species				
	Sodium + Potassium	Calcium	Chloride	Sulphate	Total dissolved solid
Ontario	0.9	1.5	2.9	2.6	9.6
Erie	0.7	1.6	2.8	2.0	8.7
Huron	0.0	0.2	1.2*	1.4	1.0
Michigan	0.0	0.0	0.5	1.3	3.2
Superior	-0.3**	0.0	0.0	0.0	-0.5**

*For the period 1940 to 1960
**Decrease due likely to changes in methods of analysis

The chloride data of Fish (1960) cover only the central and eastern basins and show an increase from 10 mg/l at Point Pelee to 15 mg/l at Buffalo. The lines of equal concentration run north-south across the lake. Results of the 1966 survey show a similar pattern but with an increase from 20 to 26 mg/l. There is also a region off the Sandusky River and Cleveland with concentrations as high as 31 mg/l. FWPCA data show average decreases in chloride concentration during the period 1963 to 1964 and 1967 to 1968 in the western and central basins averaging approximately 7 percent. The data also show a 4 percent increase in chlorides in the eastern basin for the same period. The concentrations of the various ions measured by Kramer (1961) also increase more or less uniformly from west to east. He also observed a tongue of water with a low ionic concentration at the Detroit River mouth. Generally the ionic distribution with depth is uniform, but in the western basin, at several stations, the bottom concentration of potassium is up to 10 times that at the surface. Kramer explains this anomaly by stating that high potassium values seem to predominate in sand areas where there is little clay to fix the potassium.

Results obtained by EMR during the period June to October, 1967 (Tables 2.3.8 and 2.3.9) indicate that:

(i) the concentrations of the various ions, except total iron, and conductivity are equal (within experimental limits) for the open lake stations indicating that the central and eastern basins of the lake are chemically quite uniform. This is substantiated by the chloride data of Fish (1960) and observations by the Great Lakes Institute in 1962 and 1963 and OWRC in 1966 and 1967 for that portion of the lake east of Point aux Pins,

(ii) the average concentrations in the western basin are decidedly lower than in the rest of the lake,

(iii) very much higher concentrations of all ions were recorded off Cleveland than for the rest of the lake.

Similar, though less pronounced trends, are noticeable at the mouth of the Grand River, Ontario, at the mouth of the Maumee River and at Erie, Pennsylvania.

Excluding the western basin, the deep waters of Lake Erie are rather homogeneous, vertically and horizontally, as far as the major ions are concerned, except during the summer stagnation period. This homogeneity can be explained by the current patterns of the lake and by the location of the sources of dissolved ions. There may be a small increase in conductivity from the central to the eastern basins, but a rather large change occurs in the region of Pelee Passage, where the Detroit River water mixes with the lake water. All the major constituents under normal aerobic conditions are evidently in equilibrium with the sediments except silica and phosphorus (Kramer, 1964).

The major sources of dissolved solids are the Detroit River, and the rivers running into the western basin. The contributions from the Grand (Ohio) and Cuyahoga Rivers are still substantial, but of secondary importance.

The present concentrations of dissolved inorganic solids are as yet well below the maximum allowable concentrations of the standards for drinking water of the United States Public Health Service, 1962 and the objectives of the OWRC, 1966. The waters are suitable for irrigation and, like any surface water, require treatment for domestic water supply and most industrial uses.

Table 2.3.8 Chemical characteristics at one metre depth for selected stations in Lake Erie (June 1 - Oct. 30, 1967).

	Lake Erie off Buffalo	Lake Erie off Grand R., Ont.	Mouth of Grand R. Ohio	Eastern basin off Long Point	Lake Erie off Erie	Erie harbour	Mid-lake central basin
Conductivity	319	331	567	318	320	335	316
(μmhos cm^{-1} at 25°C)							
Major ions (mg/l)							
Ca	38.7	40.9	76.5	38.3	38.3	40.2	38.4
Mg	8.0	8.4	18.8	8.0	7.9	7.9	8.0
Na	11.8	11.8	11.9	11.8	12.1	15.7	11.9
K	1.3	1.3	2.8	1.3	1.3	1.4	1.3
SO_4	25.3	28.8	79.4	25.2	25.5	30.4	25.3
Cl	25.9	25.6	20.1	25.6	26.2	31.4	25.7
HCO_3	111.4	120.5	220.3	113.1	111.0	110.1	110.3
F	0.14	0.13	0.40	0.13	0.14	0.15	0.13
Trace elements (μg/l)							
Zn	13.5	10	33	6	9	6	11
Cu	18	11	14	12	11	17	9.5
Pb	4.5	3	9	4	5	8	3
Cd	n.d.	n.d.	n.d.	1	n.d.	n.d.	n.d.
Li	2	2	5	1	1	1	1
Ni	4	4	7	2	2.5	2	2.7
Sr	157.5	218	413	150	156	168	159
Fe	121	165	940	35	84	341	100
Mn	8	10.5	113	25	8	18	7
Dissolved solids mg/l	189	198	373	188	192	198	187

Table 2.3.8 (cont'd)

	Cleveland harbour	Lake Erie off Cleveland	Northeast western basin	Western basin off Detroit R.	Toledo harbour	South central western basin
Conductivity (μmhos cm^{-1} at 25°C)	718	341	262	260	510	283
Major ions (mg/l)						
Ca	56.5	40.1	32.4	32.9	50.3	34.5
Mg	10.7	8.1	7.3	7.6	15.2	7.6
Na	63.7	13.9	8.7	9.9	26.6	9.8
K	4.9	1.4	1.1	1.1	3.6	1.3
SO_4	91.8	27.7	19.2	19.9	74.1	23.1
Cl	118.7	30.8	19.7	20.1	39.0	19.8
HCO_3	80.4	110.8	99.7	102.5	138.0	107.7
F	0.85	0.14	0.11	0.11	0.44	0.12
Trace elements (μg/l)						
Zn	45	14	10	9.5	9	12.5
Cu	11.5	17	12	12	10	15
Pb	6.5	3.3	3.8	5.5	6.5	6
Cd	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Li		3	1	1		1
Ni	16	4.5	6	4.3	22	4
Sr	255	169	127.5	123	560	169
Fe	2640	423	339	320	870	419
Mn	290	25	82	17	65	16
Dissolved solids mg/l	490	202	162	168	323	166

* n.d. - indicates none detected

Table 2.3.9 Chemical characteristics at several depths for selected stations in Lake Erie (June 1 - October 30, 1967).

Depth (m)	Eastern basin off Long Point 1	10	19	28	37	55	Midlake central basin 1	10	19
Conductivity (µmhos cm^{-1} at 25°C)	318	317	323	325	323	328	316	314	318
Major ions (mg/l)									
Ca	38.3	38.5	39.1	39.1	39.3	39.6	38.4	38.7	38.6
Mg	8.0	7.8	7.9	7.9	7.8	7.9	8.0	8.0	8.0
Na	11.8	11.5	11.8	11.9	11.8	11.7	11.9	11.8	11.8
K	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
SO_4	25.2	25.2	25.8	26.0	25.4	25.0	25.3	24.9	24.7
Cl	25.6	25.7	25.8	26.1	25.8	26.1	25.7	25.9	26.2
HCO_3	113.1	113.0	114.8	114.8	115.2	115.4	110.3	111.5	111.7
F	0.13	0.12	0.13	0.12	0.12	0.12	0.13	0.13	0.13
Trace elements (µg/l)									
Zn	6	9	13	11	9	11	11	9	15
Cu	12	12.5	10	15	16	10	9.5	19	14
Pb	4	5.5	5	4	5.5	4	3	4	6
Cd	1	n.d.	1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Li	1	2	2	1	1	1	1	1	2
Ni	2	1.5	2.5	2	2	2	2.7	2	2
Sr	150	162.5	170	162.5	155	165	159	162.5	157.5
Fe	35	43	60	63	59	86	100	80	223
Mn	25	7	7	9	9	16	7	5	19
Dissolved solids (mg/l)	188	193	193	193	195	195	187	187	189

n.d. - indicates none detected

Another way of looking at the changes in the composition of Lake Erie is to examine the changing ratios of the major cations (calcium, magnesium and sodium) and major anions (chloride, sulphate, and bicarbonate) on a triangular plot of mole percentages; e.g. moles of magnesium as a percentage of the total number of moles of the three cations (Fig. 2.3.11). The 1906 data reported by Clarke (1911); 1948 data for the water intake at Fort Erie by Thomas (1954); and the 1967 data of EMR have been compared. Although calcium still makes up over 50 percent of the cations, the percentage of sodium has increased at the expense of both calcium and magnesium. The percentage of chloride has increased mostly at the expense of bicarbonate, which still constitutes about 65 percent of the anions, whereas the percentage of sulphate is almost unchanged. Further, the rate of change is increasing, since the change from 1948 to 1967 is almost as great as from 1906 to 1948.

Historical data have also been published by Powers *et al.* (1960). Their conclusions are similar to those of Beeton (1965). Of special interest are the increases in concentrations at the outflow of Lake St. Clair to the Detroit River (Table 2.3.10).

Table 2.3.10 Changes with time in the concentrations of major ions in the Detroit River (mg/l).

	Detroit (1854)	Windsor (1948 to 1949)
Sodium + potassium	3.7	4.8
Chloride	-	6.5
Calcium	20.0	28.0
Sulphate	6.6	17.4
Total solids	98.1	131.0

Conductivity

The general distribution of conductivity gives the distribution of total dissolved solids, but cannot give the concentration of any particular ion. As calcium, magnesium and alkalinity account for some 70 percent of the ions in Lake

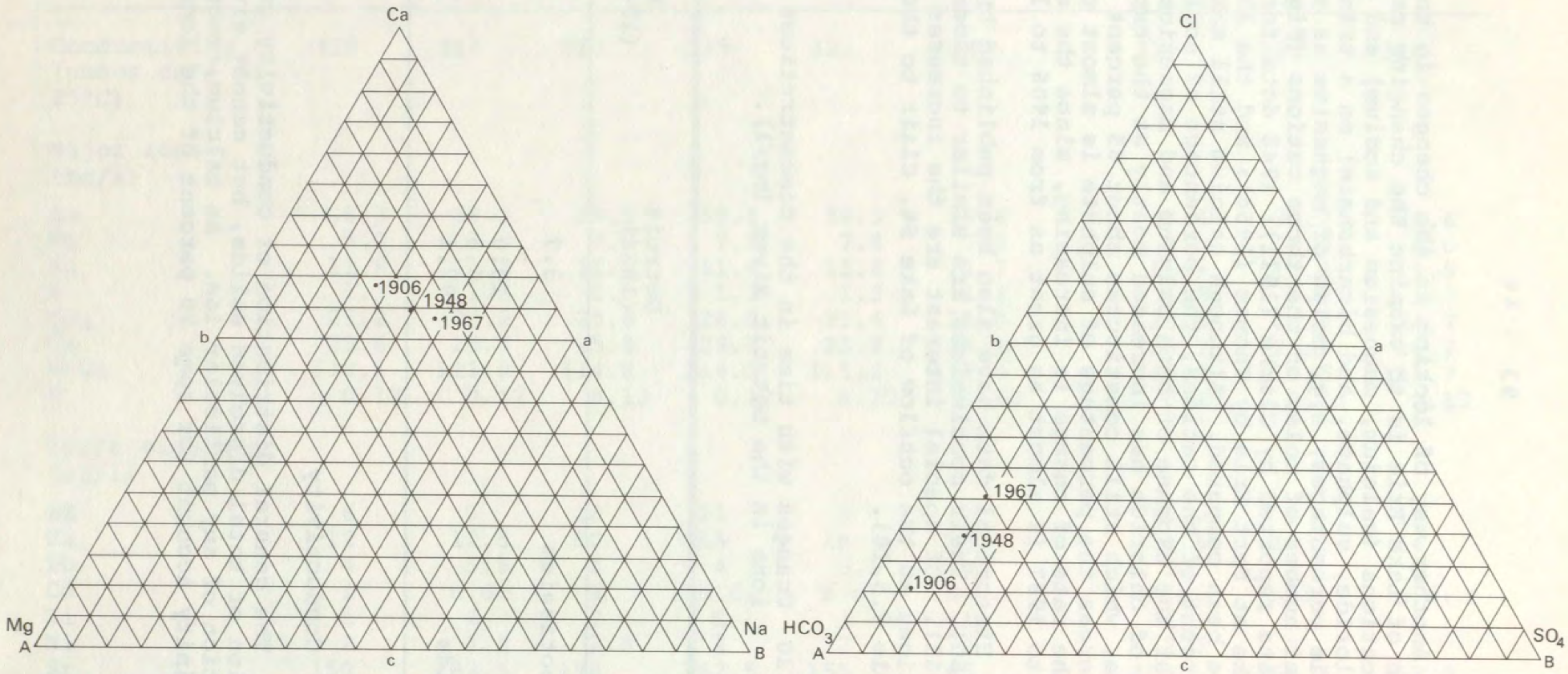


Fig. 2.3.11 Changes in the ratios of major cations and anions in Lake Erie from 1906 to 1967.

Erie, most changes of conductivity on the open lake reflect basically a change in alkalinity which in turn is due to an alteration in the calcium carbonate-carbon dioxide-water equilibrium (Kramer, 1964).

Fig. 2.3.12 shows the distribution of conductivity in the surface layer for the period July 31 to August 10, 1967. The contours of equal conductivity in the western basin are extrapolated since no observations have been made in the shallow southern region. However, a very detailed survey of this basin by Hartley *et al.* (1966) confirms the extrapolations in Fig. 2.3.12. Over the remainder of the lake the conductivity remains almost constant, except near the mouths of some rivers.

Conductivity and chloride measurements made by OWRC in 1966 to 1967 in the western basin and along the Canadian shore to Buffalo show a similar pattern. In the western basin, the conductivity is very high at the mouths of the Raisin River (700 to 1,000 μmhos cm^{-1} at 25°C) and the Maumee River (400 μmhos cm^{-1} at 25°C). In the Detroit River, the conductivity is low in the centre of the channel and increases towards its banks, particularly off the United States shore. Similarly, the conductivity increases from the centre of the lake towards the shores. Locally high conductivities are also found just west of Long Point, near the Grand River (Ohio), and Port Colborne. The distribution of chloride ion parallels that of conductivity.

Fig. 2.3.13 shows the conductivity of the water near the bottom. In the central and eastern basins, the conductivities are about 8 to 10 μmhos cm^{-1} higher at the bottom than at the surface. This can be related directly to the presence of a sharp thermocline in these basins (Fig. 2.3.14). With the development of a deoxygenated hypolimnion during the summer stagnation period, reduced forms of iron, manganese, and nitrogen, along with phosphate, and bicarbonate from the bottom sediments become soluble in the overlying water. Conductivity measurements also show increased ionic activity during the winter months at all depths with the greatest increases occurring in the bottom waters. It is apparent that some dissolved solids transfer from the sediments to the overlying waters. Examination of the distribution of conductivity over several years indicates that only when there is a well-defined thermocline in the summer months is there any difference between the average surface and bottom conductivities.

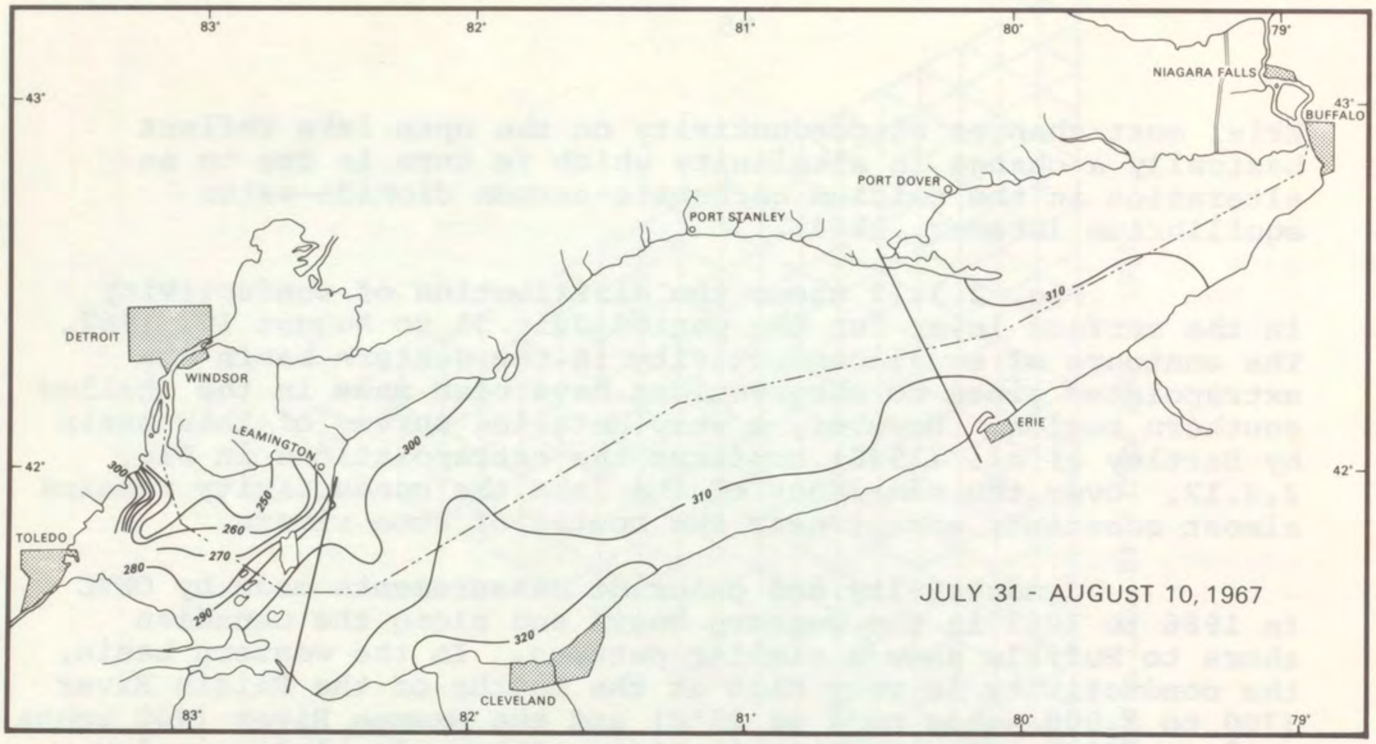


Fig. 2.3.12 Distribution of the surface conductivity (μmhos cm^{-1} at 25°C) 1967.

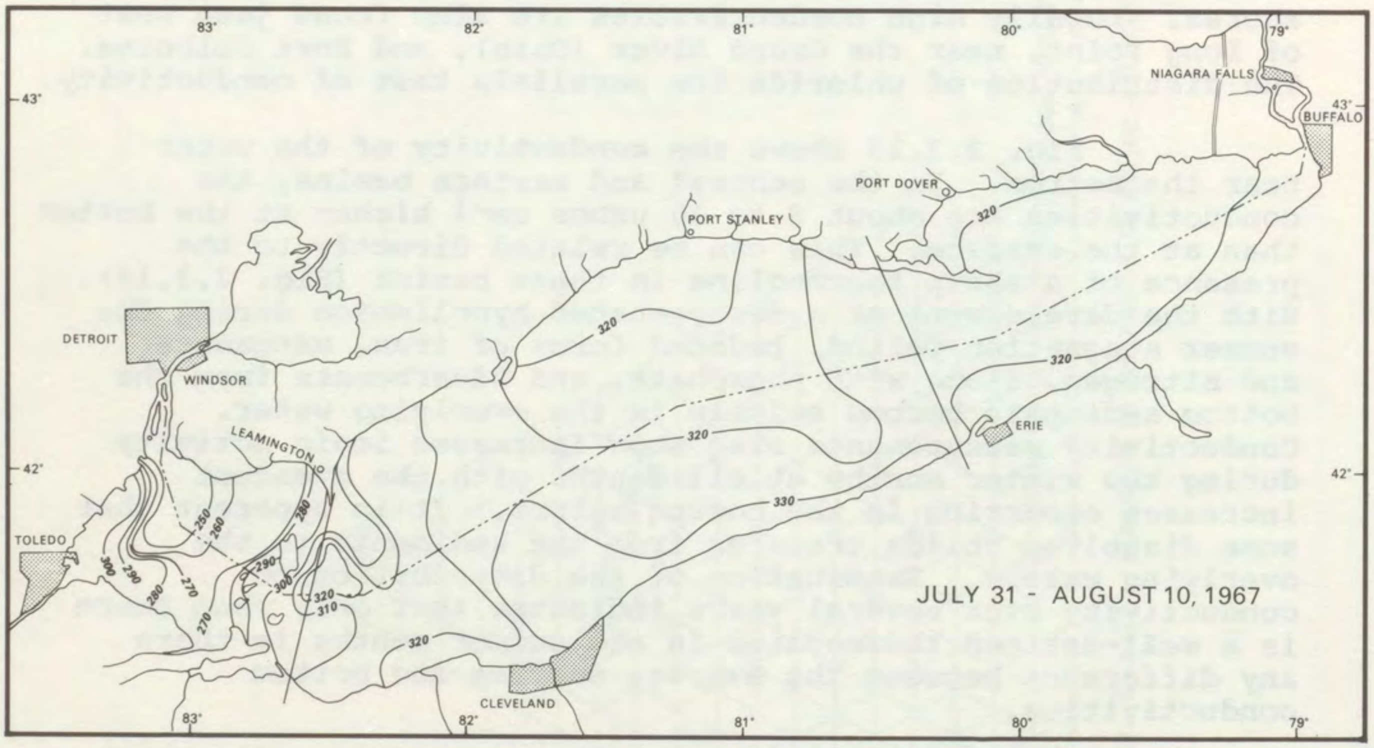


Fig. 2.3.13 Distribution of the bottom conductivity (μmhos cm^{-1} at 25°C) 1967.

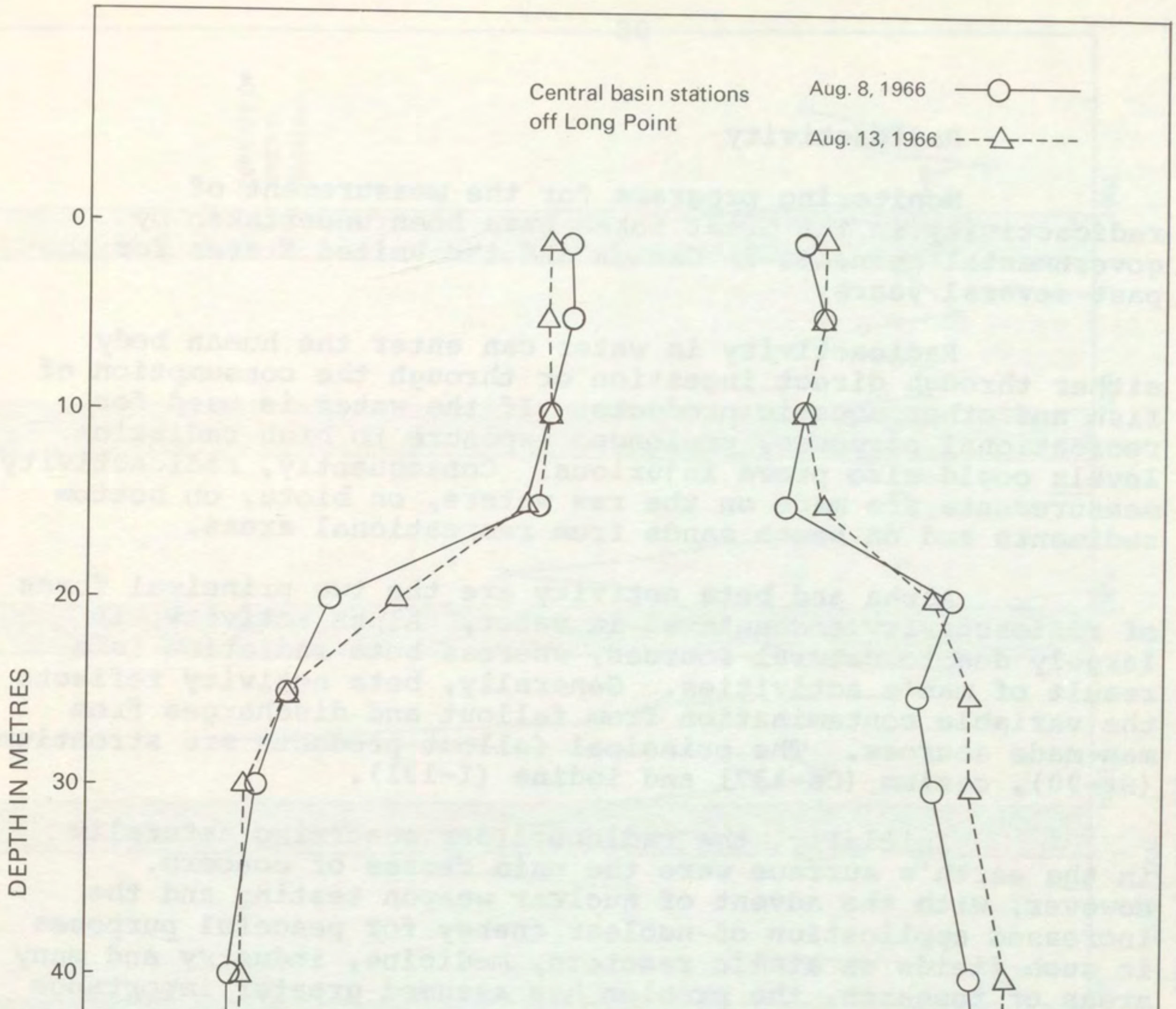


Fig. 2.3.14 Temperature (°C) and conductivity (μmhos cm^{-1} at 18°C) average of two stations in the central basin of Lake Erie, 1966.

Radioactivity

Monitoring programs for the measurement of radioactivity in the Great Lakes have been undertaken by governmental agencies in Canada and the United States for the past several years.

Radioactivity in water can enter the human body either through direct ingestion or through the consumption of fish and other aquatic products. If the water is used for recreational purposes, prolonged exposure to high radiation levels could also prove injurious. Consequently, radioactivity measurements are made on the raw waters, on biota, on bottom sediments and on beach sands from recreational areas.

Alpha and beta activity are the two principal forms of radioactivity encountered in water. Alpha activity, is largely due to natural sources, whereas beta radiation is a result of man's activities. Generally, beta activity reflects the variable contamination from fallout and discharges from man-made sources. The principal fallout products are strontium (Sr-90), cesium (Cs-137) and iodine (I-131).

Initially, the radionuclides occurring naturally in the earth's surface were the main causes of concern. However, with the advent of nuclear weapon testing and the increased application of nuclear energy for peaceful purposes in such fields as atomic reactors, medicine, industry and many areas of research, the problem has assumed greater importance in recent years. In the case of Lake Erie, the main source of radioactivity is from fallout following nuclear weapon testing. Fallout radionuclides can enter bodies of water directly through precipitation and dry fallout, or through runoff and leaching of radioactivity deposited on the soil. The greatest percentage of fallout occurs with the spring rains after periods of active fallout. This is well demonstrated in Fig. 2.3.15, where total beta activity at Hamilton is plotted for the period July 1958 to December 1965. Radioactive wastes from nuclear reactors, waste processing plants and from industrial, medical or research uses are either discharged directly or through municipal sewers. On entering the water, the radionuclides are diluted and distributed by vertical and horizontal mixing. This dilution effect would be greatest in large lakes, hence relatively low levels of radioactivity are found in such bodies of water.

The amount of radioactivity that can be discharged to surface waters by nuclear reactors or other operations is carefully controlled by governmental regulations. As an example

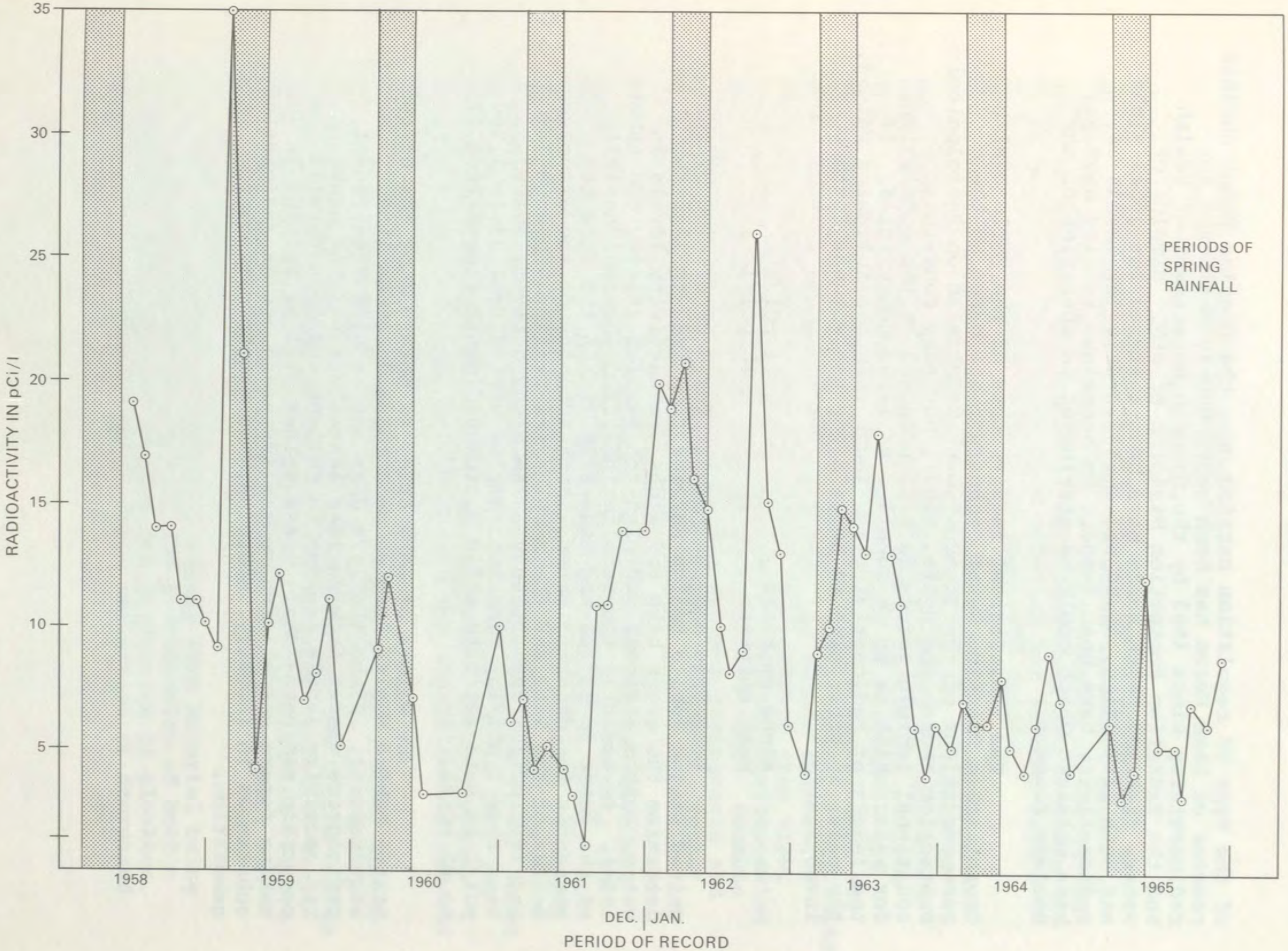


Fig. 2.3.15 Total beta radioactivity in pCi/1, measured by the Hamilton Municipal Laboratory, 1958 to 1966.

of the type of regulation carried out, the Douglas Point nuclear reactor on Lake Huron has been continuously monitored for radioactivity since 1963 by the Ontario Department of Health and the Radiation Protection Division of NHW. Samples of water, fish and beach sands have been analyzed for gross alpha and beta activities, Sr-90 and Cs-137. Only low levels of radioactivity have been found. No anomalous results have yet been obtained which could be attributed to operation of the nuclear reactor.

The radiological requirements of the World Health Organization Drinking Water Standards, are based on the recommendations of the International Commission on Radiological Protection (McKee and Wolfe, 1963), but they contain an additional tenfold safety factor, proposed by the Commission, for water which is to be supplied to large communities. If the levels of radioactivity are lower than the following values, the water is considered to be safe for use without further investigation:

alpha emitters	1 pCi/l
beta emitters	10 pCi/l

Lake Erie and its tributaries were studied by the United States Public Health Service from 1963 to 1965 to determine the gross beta and alpha radioactivity levels in water, bottom sediment and plankton samples (Risley and Abbott, 1966). In general, the results indicated the radioactivity of the water to be low and generally within the accepted standards for drinking water. Beta activity of the dissolved solids of the lake and the sampled tributaries averaged 7.9 and 14.3 pCi/l, respectively. The alpha activity averaged less than 1 pCi/l. Plankton samples varied from 33 to 1,200 pCi/l in beta activity while bottom sediments ranged from 11 to 81 pCi/l.

The waters of Lake Erie, as observed by the United States Public Health Service meet these water quality requirements. Since the lake does not receive significant radioactive wastes from nuclear installations, the above radioactivity levels are due to fallout and/or naturally occurring radionuclides. These values will be helpful in making future comparisons on the increased use of radioactive substances in industry, medicine, and electrical power generation.

2.3.5 Other Characteristics

Turbidity and Colour

Turbidity describes the degree of opaqueness of water. It expresses the extent to which suspended matter in water inhibits the penetration of light because of scattering and absorption. The degree of turbidity does not indicate the types of substance present in a solution but it does have a relation to the concentration of suspended solids.

Turbidity measurements are commonly made using a Jackson Candle Turbidimeter, bottle standards, a Turbidity Rod, or optical instruments. Turbidity values are expressed in three numerically equivalent systems: parts per million (ppm), or Jackson Turbidity Units (JTU), as defined by the American Public Health Association (1965). A Secchi disc may also be used to give an approximation of the degree of turbidity. The lower the turbidity of the water, the deeper this white circular disc may be lowered before disappearing from view. Secchi disc measurements are recorded in metres, corresponding to the depth of apparent disappearance of the disc. Because turbidity observations vary markedly between instruments and observers, their value lies in relative differences, rather than absolute values.

Light penetration into water is highly dependent upon the turbidity. The relation of light intensity to the photosynthetic rate was studied by Verduin (1954, 1956). As the growth of plankton depends upon the availability of light, turbidity could be one of the important physical factors affecting plankton production. Meyer and Heritage (1941) found that during times of low turbidity, light was not a limiting factor for photosynthesis but during periods of fairly high turbidity, the rate of photosynthesis was significantly reduced even at depths less than 1 metre.

Game fish which feed by sight are at a disadvantage in dark waters compared to coarser types such as carp and catfish (Tarzwell, 1957). For domestic usage the United States Public Health Service (1962) has set an upper turbidity limit of 5 JTU for finished drinking water. Many industries require water supplies with a turbidity of 10 JTU or less (Fair and Geyer, 1954).

Increases in turbidity result from material being carried into the lake by rivers, the resuspension of bottom sediments, shore erosion or from the production of plankton. Conversely turbidity decreases are a reflection of decreased river discharges or a decrease in the plankton crop. Van Oosten (1948) suggests that the effects of wind are the predominant factors affecting turbidity.

Annual Cycle

In Lake Erie, two pulses of high turbidity and two periods of low turbidity occur annually (Powers *et al.*, 1960; Chandler, 1940). During the period of ice cover, the waters become less violently agitated and the turbidity declines. The spring pulse of high turbidity occurs between April and June as a result of wind, spring runoff, and an early plankton bloom (diatoms). When the runoff decreases and winds subside a low summer turbidity develops as suspended materials settle to the bottom. As autumn approaches, freshening winds cause a resuspension of sediments which, together with a fall plankton bloom (blue-greens) give rise to increased turbidity (Fig. 2.3.16). The autumn turbidity values generally are lower than spring values since autumn runoff is usually minimal. With the reformation of ice, the turbidity again decreases to the winter-early spring low.

Vertical Structure

Turbidity does not vary significantly with depth. The vertical turbidity structure during 1967 across a section of Lake Erie (Fig. 2.3.17) illustrates a number of minor maxima and minima, particularly a small vertical variation, and simple structure during the summer, as compared with the autumn observations. The temporal and spatial range of turbidity in July exceeds the vertical variation with the exception of the vertical range found in the deep eastern basin.

Pinsak (1967) stated that water transparency in the hypolimnion is much less than in the upper waters. He interpreted the decrease as evidence of an increase in turbidity. The 1967 observations by EMR show that at a given location, the deepest sample, usually within 4 metres of the bottom, was the most turbid for half of the measurements. When thermal stratification was present the bottom water was slightly more turbid than the near surface water in over 75 percent of the observations. This is believed to be due to the resuspension of bottom sediments by gases generated from anaerobic decomposition and to the movement of the hypolimnion.

Horizontal Distribution

The relative distribution of turbidity values at 1 metre depth is depicted in Fig. 2.3.18. Relatively high values

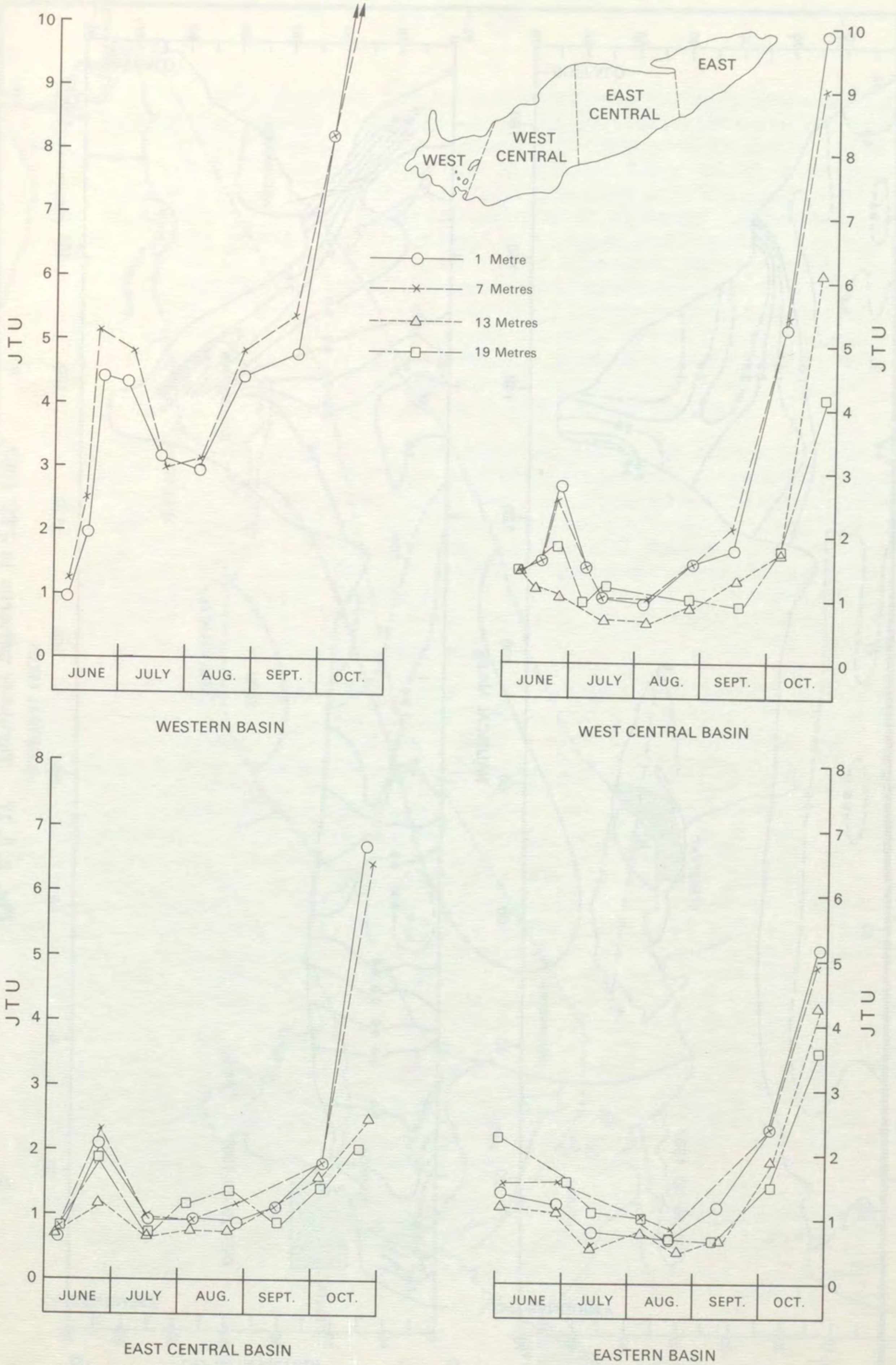


Fig. 2.3.16 Mean turbidity curves for the summer and autumn of 1967.

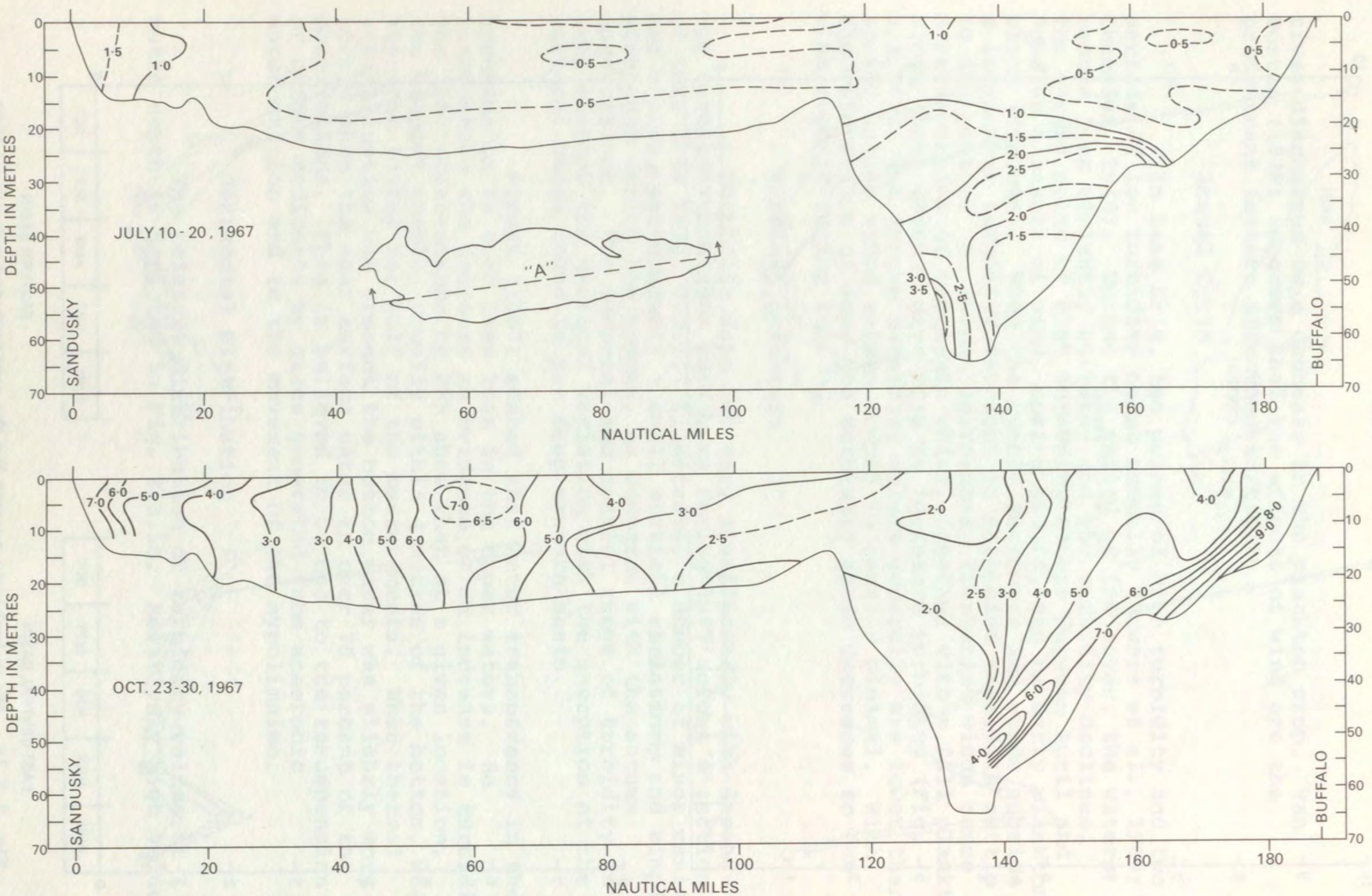


Fig. 2. 3. 17 Turbidity patterns in JTU 1967.

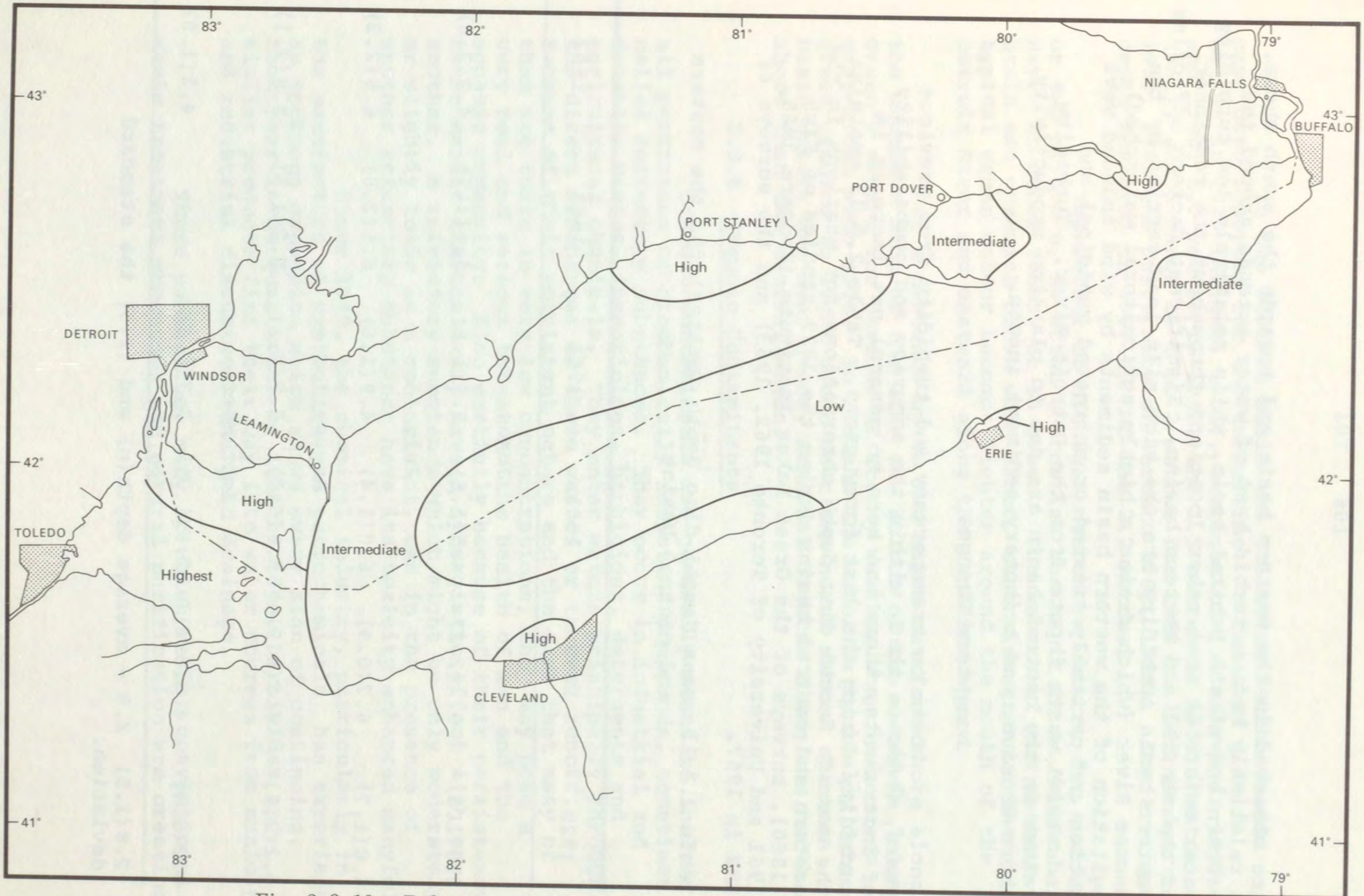


Fig. 2.3.18 Relative turbidity distribution, at 1 metre depth, 1967.

are observed in the western basin and towards the south shore. A relatively medium turbid band of water extends around the western end of the central basin, while relatively low turbidity water exists at most other locations throughout the remainder of the central and eastern basins. Significant factors affecting western basin turbidity are the high silt load carried by the Maumee River (which drains a highly agricultural watershed), agitation of the western basin sediments by wind induced wave action and partially treated or untreated municipal and industrial waste inputs from the Detroit River. Turbidity values in the central basin are due to plankton productivity, shore erosion, and tributary sediment inputs.

Long-term Changes

Data on transparency and turbidity from previous years, indicate that, within the accuracy and comparability of instruments, there has been no general net increase in turbidity during the last forty years. Table 2.3.11 contains the average Secchi disc depth observations for stations in the eastern and central basins during the 1929 studies of Fish (1960), surveys of the Great Lakes Institute (Rodgers 1960, 1961 and University of Toronto 1962, 1963) and the surveys of EMR in 1967.

Table 2.3.11 Mean Secchi disc depth (metres) for the eastern and central basins.

1929	1960	1961	1962	1963	1967
			June		
2.8(1.5)[1]	6.1(2.2)	4.5(1.5)	6.9(1.8)	4.4(1.5)	4.9(2.0)
			July		
4.0(1.7)	6.7(0.9)	6.8(1.4)	4.9(1.6)	6.5(2.0)	6.8(2.2)
			August		
4.2(2.1)	6.3(0.9)	5.9(0.9)	5.9(0.5)	5.2(1.5)	5.9(2.1)
			September		
6.2(3.4)	4.8(3.4)	2.6(1.3)	3.7(1.3)	-	4.3(1.5)

[1]2.8(1.5) 2.8 - average depth(m) and (1.5) the standard deviation.

In the western basin the following Secchi depths have been reported for the summertime: a range of 1 to 2 metres in 1929 (Wright, 1955), averages of 1.1 metres in 1939 and 1940, 1.7 metres in 1941, and 1.5 metres in 1959 (Beeton, 1961), and a range of 1 to 2 metres for 1960 to 1963 (Rodgers 1960, 1961 and University of Toronto 1962, 1963). The average depth measured in 1967 by EMR was 2.2 metres.

The colour of Michigan nearshore waters, for a mile or two offshore, is often a brownish hue as it is in Maumee Bay. At other times, it is green. The waters of the western basin are greenish-brown when mixed, otherwise green. The typical green colour becomes lighter around the mouth of the Detroit River and eastward along the Canadian shore.

For a distance up to two miles out from shore along the southern side of the lake the colour of the water is "algae-green", except for periods of stormy weather when it becomes gray-brown with silt. In midlake the water is typically deep green grading to light green near the north shore. Eastern basin waters are deep green, somewhat lighter along the north shore than the central basin.

2.3.6 Organic Contaminants

Organic contaminants are generally meant to include all persistent or biochemically resistant compounds, sometimes called refractory substances. They occur in industrial and domestic wastes, insecticides, herbicides, detergents and agricultural chemicals. They enter waters principally through the direct discharges of these wastes or through runoff. Because of their persistent nature and the fact that many of them are toxic in very low concentrations, they may pose a very real and serious threat to the health of man and the aquatic community. Also partially because of their persistency, these exotic chemicals may have a synergistic effect with one another. A refractory substance which might be only moderately or slightly toxic as a contaminant, can in the presence of another refractory substance have its toxicity enhanced manyfold.

Since 1940, the chemical industry, particularly in the manufacture of synthetics and petrochemicals, has experienced an enormous expansion which shows every sign of continuing. Each year large quantities of insecticides, herbicides and similar products find their way into water courses from municipal and industrial discharges, and land drainage.

These substances, many of which resist conventional waste treatment processes and natural purification are creating problems in public and industrial water supplies. Fish kills caused by certain organic contaminants have been reported, and in some cases, though contaminant levels have not been high enough to cause death, they have been sufficiently high to seriously affect fish fertility.

Without adequate waste treatment, the inevitable increase in water re-use will cause these organic contaminants or refractories to build up with a consequent deterioration in water quality. The problem is further complicated by the fact that a lack of information on levels of these compounds exists for surface waters, including the Great Lakes. Further analytical techniques for these substances at their low concentrations are at best time-consuming and cumbersome. The most common way of reporting organic contaminants in water is in terms of micrograms per litre (μg/l) of carbon chloroform extract (CCE). Because of the possible low recovery efficiencies of the CCE test, reported values may be less than the actual values.

Since it is extremely difficult to analyze and define the chemical and toxicological nature of these materials, it is a desirable objective that CCE be maintained at a low level. At concentrations of about 200 μg/l, unfavourable tastes and odours can be detected in water. In comparison, clean surface and ground waters contain about 25 to 50 μg/l of CCE. Highly coloured water may have somewhat higher concentrations, due to lignins, tannins, humates, etc. The most desirable condition is one in which the water supply to the consumer contains no organic residues.

Some data on CCE in the Great Lakes basin have been accumulated by FWPCA. Table 2.3.12 summarizes these data for 1962 and 1963.

The United States Public Health Service Drinking Water Standards (1962), limit the amount of CCE in water to 200 μg/l. This is also the objective of the OWRC for potable waters under their jurisdiction. In most cases, including the source water for Lake Ontario, Lake Erie at Buffalo, and the St. Lawrence River at Massena, New York the observed CCE values are of the same order as those generally found in clean surface and ground waters. The recent observations near Metropolitan Toronto are higher than desirable but still within current objectives.

Table 2.3.12 Maximum concentrations of organic contaminants (CCE) in the Great Lakes basin, October 1, 1962 to September 30, 1963 - recovered by carbon filter technique, (After United States Public Health Service), results in μg/l.

Location	Month	Sampling intervals in days	Gallons filtered	Carbon chloroform extractables μg/l
St. Lawrence R. Massena, N.Y.	September	15	4,660	54
Lake Erie Buffalo, N.Y.	July	8	4,590	66
Detroit R. Detroit, Mich.	June	14	4,890	39
Lake Michigan Milwaukee, Wisc.	August	8	2,707	45
St. Mary's R. Sault Ste. Marie, Mich.	July	14	2,460	67
Lake Superior Duluth, Minn.	June	14	5,100	33

Pesticides and Herbicides

Pesticides are another form of organic contaminant which deserve particular attention. Since the introduction of DDT as an insecticide during World War II, the use of organic pesticides has increased enormously. In 1961, it was estimated that more than 9,000 commercial pesticide preparations were available in the United States. Certainly a large number are available today. Many such compounds resist degradation and when applied to foliage, soil, and water courses, are translocated into rivers and their tributaries. Furthermore, heavy concentrations can contribute characteristic odours to water supplies and taint the flesh of fish since may of these herbicides and insecticides are highly odourous.

Herbicides and insecticides can reach potable water supplies from aerial spraying, runoff from agricultural areas, percolation through the soil to underground supplies, municipal waste discharges, and from such food processing industries as canneries. Tests have demonstrated that some of these compounds can persist in the soil for longer than five years. Accumulations of such chemicals would not, therefore, be expected to reach water supplies in large amounts from meadows, pasture lands, or other well-sodded areas. The greatest potential contribution of herbicides and insecticides by runoff is probably associated with erosion of cultivated or plowed areas.

In certain areas herbicides and other chemical control agents are added directly to the water in order to control nuisance aquatic growths. Under the OWRC Act, permits are required for such application. The chemicals approved by the OWRC for application to water are tested extensively for effects on fish and other aquatic life prior to use. Since the inception of this program in 1962, a total of 937 permits have been issued. The quantities applied to the lower Great Lakes basin are reported in the Lake Ontario Volume.

Only Pennsylvania and Michigan on the United States side have similar controls over the application of herbicides directly to water.

The commercial applications on land, particularly in the tobacco growing areas in the western Lake Erie drainage area, far outweigh the amounts used in water. However, detailed data on applied quantities are not available. There have been few instances in Lake Erie where water quality impairment problems, in particular fish kills, have been traced to pesticide application on land.

Studies in the United States have revealed the presence of pesticides in the major rivers and lakes of the nation (Breidenbach *et al.*, 1967). Those measured were generally found in concentrations of less than 1 μg/l and they were usually the persistent chlorinated hydrocarbon insecticides.

Studies of pesticide levels in the Lake Erie basin have been carried out by the USPHS and Department of the Interior since 1958. Dieldrin has been observed in the St. Clair River from 1960 to 1962 and in Lake Erie at Buffalo consistently over the period from 1958 to 1964. From Table 2.3.13 it is evident that some pesticides have been detected at Buffalo, New York, Toledo, Ohio and in the Detroit and St. Clair Rivers. Dieldrin has dominated pesticide occurrences over the years 1958 through 1965 (Breidenbach *et al.*, 1967). Generally, the presence of pesticides, if not their absolute values, have been observed with greater frequency in recent years.

In 1964, FWPCA examined twenty-one Lake Erie bottom sediment samples for chlorinated hydrocarbons. In contrast to sulphur and phosphorus pesticides, the chlorinated hydrocarbons do not hydrolyze and revert to innocuous forms. As a result, accretion on a proper adsorbent substrate could be expected. Positive identification of DDT was made at two stations, and DDE at one station, all in midlake. The concentration of DDT ranged from 0.46 μg/l to 1.11 μg/l. The concentration of DDE was 1.31 μg/l. Since bottom sediments absorb pesticides from overlying waters it is reasonable to assume that the concentration of pesticides in the overlying waters is much less than found in sediments.

DDE Residues in Fish

The OWRC collected fish from the western, central and eastern basins of Lake Erie between November 1965 and October 1967. Since DDT was considered to be the most commonly used insecticide of the chlorinated hydrocarbon group, a limited number of analyses were completed to provide preliminary information of the accumulation of this insecticide in fish collected from Lake Erie.

These data are summarized in Table 2.3.14 and are reported as DDE, a derivative of DDT. The DDE values for yellow walleye, common white suckers and sheepshead collected in the western basin were low, all less than 1 mg/kg except for one gonad sample from a female yellow walleye. The concentrations of DDE in the ovaries of the yellow walleyes were found to be approximately four times greater than in the

Table 2.3.13 Concentrations of chlorinated hydrocarbon pesticides (μg/l) in Great Lakes waters, September 1965 (After Breidenbach *et al.*, 1967).

Location	Concentrations in micrograms per litre								
	Dieldrin	Endrin	DDT	DDE	DDD	Aldrin	Heptachlor	Heptachlor epoxide	BHC
St. Lawrence River Massena, N.Y.	n.d.	n.d.	n.d.	n.d.	.010	n.d.	.031	.017	n.d.
Lake Erie Buffalo, N.Y.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	.002	n.d.
Maumee River Toledo, Ohio	.024	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Detroit River Detroit, Mich.	.018	n.d.	n.d.	.008	n.d.	n.d.	.015	p	n.d.
St. Clair River Port Huron, Mich.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Lake Michigan Milwaukee, Wis.	.003	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Lake Superior Duluth, Minn.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. - indicates none detected

p - data are reported as presumptive in instances where the results of chromotography were highly indicative but did not meet all requirements for positive identification and quantification

Table 2.3.14 Maximum, minimum and mean DDE values (mg/kg fresh weight) for fish samples of Lake Erie (Ontario Water Resources Commission).

Species	No. of fish in sample	Sex	Tissue[2]	Result[1] max.	min.	mean
		Lake Erie - Western basin				
Yellow Walleye	6	M	M	0.26	0.07	0.19
			G	0.29	0.03	0.17
	5	F	M	0.51	0.12	0.17
			G	1.20	0.52	0.82
	2	undetermined	whole fish (comp)	-	-	0.35
Common White sucker	3	M	whole fish	0.61	0.15	0.31
Sheepshead	4	3 M	whole fish			
		1 F	(comp)	-	-	0.23
		Lake Erie - Central basin				
Yellow Walleye	6	3 M 3 F	whole fish	0.39	0.28	0.33
Yellow Perch	34	16 M	M(comp)	0.07	0.05	0.06
		18 F	G(comp)	0.41	0.29	0.35
		Lake Erie - Eastern basin				
Yellow Perch	7	4 M	M	0.13	0.08	0.11
			G	4.70	0.15	1.68
		2 F	M	0.10	0.09	0.10
			G	0.85	0.78	0.81
		1 F	whole fish	-	-	1.00
White bass	2	F	M(comp)	-	-	0.19
			G(comp)	-	-	0.40
Sheepshead	4	1 M	M	-	-	0.25
			G	-	-	0.27
		3 F	M	0.50	0.15	0.32
			G	0.65	0.51	0.58

[1]In this study a saponification procedure was used to extract pesticides from the fish tissue. Any DDT present was converted to DDE, the DDE remained unchanged, but any DDD present was completely destroyed. The use of this saponification procedure provided a rapid quantitative and qualitative screening technique. Therefore, values reported as DDE include DDT and DDE, but not DDD.

[2]M - muscle tissue
G - gonads

muscle tissue of the same fish. Concentrations in the muscles and gonads of 6 male walleyes were similar.

Yellow walleye and yellow perch were also collected from the central basin. In a sample of yellow perch of mixed sexes the gonadal composite contained almost six times as much DDE as did the muscle taken from the same fish. However, each of the composite results was less than 0.5 mg/kg.

In the eastern basin yellow perch, white bass and sheepshead were sampled. Results were again generally less than 1 mg/kg and as in the other basins, concentrations in the gonadal tissue were considerably higher than in the muscle tissue. However, in absolute terms the concentrations found were generally low. Both the white bass and the sheepshead samples contained low concentrations of DDE. The concentrations found in the sheepshead samples of both the eastern and western basins were similar.

In summary, the DDE concentrations found in the fish samples from Lake Erie were usually less than 1 mg/kg. Values ranged from 0.03 mg/kg DDE in the ovaries of a yellow perch from the western basin to 4.70 mg/kg DDE in the ovaries of a yellow perch from the eastern basin. While the numbers of fish collected were small there would appear to be no distinct pattern in the distribution of DDT in fish throughout the lake. Concentrations of DDE found in the gonads were consistently higher than those found in the muscle tissues. From the available data, there appears to be little inter-specific variation in DDE residue levels.

Data from studies conducted by the United States Bureau of Commercial Fisheries and Michigan State University in Lake Erie from 1965-1967 are reproduced in Table 2.3.15. These data further support the observations of the OWRC. The Great Lakes Fishery Commission has made the following observations regarding general findings concerning DDT in Great Lakes fishes:

1. Great Lakes fishes contain significant quantities of DDT residues as high as 10.4 mg/kg in chubs (*Coregonus hoyi*), even higher concentrations have been observed by OWRC in the testes of a male northern pike in Lake Ontario.

2. DDT levels in Lake Michigan fish are two to five times higher than in fish from other Great Lakes.

Table 2.3.15 Pesticide residues in whole fish from Lake Erie, 1965 to 1967.

Species	Number of fish	Number of analyses	Method[1]	Pesticide concentration mg/kg fresh weight						
				Dieldrin	o,p-DDT	p,p-DDD	p,p-DDE	p,p-DDT	p,p-DDE p,p±DDT	Total DDT[2]
Alewife	27	6	H	–	.13	.69	.32	.44	.78	1.59
		6	S	.14	–	–	–	–	.99	–
American smelt	8	1	H	–	.22	.19	.27	.60	.87	1.28
		1	S	.04	–	–	–	–	.72	–
		1	E	–	–	–	–	–	–	.84
Brown bullhead	7	1	H	–	.00	.11	.06	.04	.10	.21
		1	S	.00	–	–	–	–	.18	–
		1	E	–	–	–	–	–	–	.34
Emerald shiner	6	2	H	–	.15	.75	.44	.21	.65	1.55
		1	S	–	–	–	–	–	.03	–
Gizzard shad	9	2	H	–	.02	.26	.08	.17	.26	.53
		2	S	.08	–	–	–	–	.30	–
Freshwater drum	12	2	H	–	.12	.42	.22	.25	.48	1.01
		2	S	.04	–	–	–	–	.32	–
		2	E	–	–	–	–	–	–	.54
Goldfish	2	1	E	–	–	–	–	–	–	.70
Spottail shiner	9	3	E	–	–	–	–	–	–	.25
Stonecat	2	1	E	–	–	–	–	–	–	.28
Walleye	47	5	H	–	.12	.61	.40	.38	.79	1.52
		5	S	.09	–	–	–	–	1.75	–
		27	E	–	–	–	–	–	–	1.01
White bass	3	1	H	–	.23	.22	.50	.94	1.44	1.89
		1	S	.04	–	–	–	–	1.32	–
White sucker	3	1	H	–	.00	.11	.10	.16	.26	.37
		1	S	.02	–	–	–	–	.19	–
Yellow perch	212	4	H	–	.06	.32	.28	.38	.65	1.08
		4	S	.05	–	–	–	–	.57	–
		22	E	–	–	–	–	–	–	.75

[1]H - homogenized; S - saponification; E - ether extraction
[2]DDD + DDE + DDT

3. DDT levels in eggs and fry of rainbow trout and Coho salmon from Lake Michigan are similarly two to five times higher than in eggs and fry of these species from Lake Superior and Oregon.

4. Death of 700,000 Coho fry hatched from eggs produced by Lake Michigan Coho displayed the same characteristics as did the death of fry exposed to lethal DDT levels; fry produced from eggs taken from Lake Superior and Oregon Coho did not suffer unusual losses during development.

5. Moribund fry from Lake Michigan Coho had significantly higher DDT levels than surviving fry from Lake Michigan.

The Commission further stated its belief that the observations provide sufficient evidence to indicate that DDT residues in certain important Lake Michigan fish are already affecting reproduction and are a serious threat to the rehabilitation of the fishery resources of that lake.

Though levels in Lake Erie are not as high as those observed in Lake Michigan, they are persistent and therefore a matter of importance in pollution control planning.

Phenols

During the past 20 years a great deal of interest has been shown in the phenol concentrations throughout the Great Lakes system, because of the taste and odour effects of phenols in water supplies.

From 1948 to 1949, inshore stations had concentrations as high as 500 µg/l phenol at the head of the Niagara River, and off Buffalo where evidence of gross pollution was found in localized areas. The entire portion of the lake surveyed, between Crystal Beach, Ontario, and Buffalo, New York, however, had an average concentration of 10.2 µg/l. In 1955, after significant phenolic reductions in industrial wastes were achieved maximum levels of 9 to 10 µg/l phenol were found with the average for the same area being only 2 µg/l.

Phenol results obtained from lake-wide water samples taken on Lake Erie in 1967, ranged from 0 to 17 µg/l. The median value and average for the whole lake from all cruises was 2 µg/l phenol.

A direct comparison of phenol values obtained from individual stations from 1948, 1955 and 1967, is difficult due to the variations in the sampling station locations. However, based on results obtained from previous years as well as current analyses, there would appear to have been a steady reduction of phenol levels in Lake Erie over the past 19 years.

2.4 BIOLOGY

The structure and composition of plant and animal communities within a particular lake environment result from the interaction of chemical, physical and biological factors, both within and outside the lake basin. Since lakes are receiving basins for materials carried by rivers and streams, the nature of the substrate and the chemical characteristics of the impounded waters are influenced by the geochemical make-up of the watershed. These factors, in addition to the morphometry of the basin, current patterns, wave action, temperature and light, are important parameters affecting the distribution patterns and population dynamics of biological communities in lakes.

This section of the report combines a historical review of aquatic biological data with more recent information provided by the FWPCA and the OWRC. Additional information on benthic communities was provided by the Fisheries Research Board of Canada and the Great Lakes Institute of the University of Toronto. A section summarizing the present status and the past changes in the fisheries of Lake Erie over the years has been compiled from information prepared by the United States Public Health Service (based on records from the United States Bureau of Commercial Fisheries) and the Ontario Department of Lands and Forests.

For comparative purposes, the lake was divided into the western, central and eastern basins, adopting the divisions used by Davis (1966).

2.4.1 Phytoplankton

Planktonic algae are the primary producers of organic matter in lakes, converting the sun's energy into chemical compounds that in turn are used as food by animals and non-photosynthetic micro-organisms. Phytoplankton production and distribution are influenced by sunlight, temperature, size, shape and slope of the lake basin, type of substratum, water movements, grazing by zooplankton, nutrients, and other factors.

Many inorganic elements are required for algal cell growth, including nitrogen, phosphorus, potassium, calcium and iron. Provasoli (1958) indicated that vitamin B_{12}, thiamine, and certain other organic compounds are also necessary for the growth of some algae. Algae reproduce rapidly when phosphate is added to the water, and continue to reproduce as more phosphorus is added. However, nitrogen and other nutrients must also be present if algal production is to continue. Sawyer (1954) concluded that when inorganic nitrogen concentrations of 0.30 mg/l (sum of NH_3-N, NO_2-N and NO_3-N) and orthophosphate-phosphorus concentrations of 0.01 mg/l (PO_4-P) were present in bodies of water at the start of the active growing season, nuisance algal blooms could be anticipated. Mackenthen (1965) suggested that the initial stimulus for algal production is supplied by dissolved phosphorus and that a continued high rate of nutrient supply does not appear to be necessary for sustained algal production. Re-cycling of nutrients within the lake basin may be sufficient to promote algal blooms for several years.

Knowledge of the species of algae found in lakes is important for an understanding of the eutrophication process, and for an evaluation of the general water quality of a lake. Certain species of the Chlorophyceae (green algae), the Chrysophyceae (yellow-brown algae), and Bacillariophyceae (diatoms) are common in oligotrophic lakes. On the other hand, some of the euglenoids, blue-greens, and other species of diatoms appear most often in the nutrient enriched waters of eutrophic lakes. Species of *Anacystis*, *Aphanizomenon*, *Stephanodiscus*, *Melosira* and *Fragilaria* often predominate in eutrophic lakes.

Algae interfere with water-oriented recreational activities, impair the aesthetic qualities of the water, are responsible for filter-clogging, taste and odour problems, and affect coagulation and sedimentation processes.

Most of the early phytoplankton studies in Lake Erie were taxonomic in nature, including those of Vorce (1881, 1882), Tiffany (1934, 1937), Taft (1942, 1945, 1964) and Hohn (1951). The majority of these authors agree that the standing crop of phytoplankton in the lake is characterized by vernal and autumnal maxima, and winter and summer minima. Variations from this pattern have been described by Gottschall and Jennings (1933), Chandler (1940, 1942a, 1944), Davis (1954a, 1964) and Williams (1962). Chandler and Weeks (1945), in evaluating the phytoplankton populations between 1938 and 1942 around the Bass Island region of Lake Erie indicated that these variations were related to physical changes such as temperature, turbidity and solar radiation rather than chemical changes. Most authors have reported a dominance of diatoms during the winter, spring and late fall seasons. Verduin (1960), however, found the flagellate *Chlamydomonas* to be important during the winter months.

Between 1928 and 1951, the summer standing stocks of phytoplankton were dominated by the diatoms. More recent studies (Verduin, 1960; Davis 1962) have indicated an increasing representation of flagellates, especially *Ceratium hirundinella*, and the green *Pediastrum* during the summer and fall period. Tiffany (1958) and Casper (1965) reported on the "water-blooms" of blue-green algae in the western basin of Lake Erie. Davis (1964) showed clear evidence of eutrophication based on qualitative and quantitative changes in the composition of standing stocks of phytoplankton at the Division Avenue Filtration Plant of the Cleveland Division of Water and Heat, at Cleveland, Ohio. From data accumulated by Saunders (1964) it is evident that photosynthetic production in the western basin of Lake Erie is higher than in any other open water area of the Great Lakes.

The present report deals mostly with recent phytoplankton analyses on samples obtained regularly at waterworks along the Canadian shore of Lake Erie and auxiliary nearshore and offshore samples obtained by the OWRC together with lake-wide data obtained by the FWPCA. Some chlorophyll a measurements are also included.

For the period March, 1966 through November, 1967, phytoplankton analyses were completed by the OWRC on weekly samples from six municipal waterworks intakes along the northern shore of Lake Erie. For comparative purposes, samples were obtained from intakes at Sarnia on the St. Clair River and at Windsor on the Detroit River. Fig. 2.4.1 and Table 2.4.1 show the location, length and depth of the respective intakes. Supplementary samples were collected at both nearshore and offshore locations.

The United States Public Health Service and the FWPCA collected data on phytoplankton populations at offshore locations during summer cruises in 1963, 1964, 1967 and 1968.

Results

The yearly average standing crop of phytoplankton was measured at Sarnia, Windsor and six Lake Erie waterintakes on the Canadian shore. All values cited below have been rounded off to two significant figures. At Kingsville, in the western

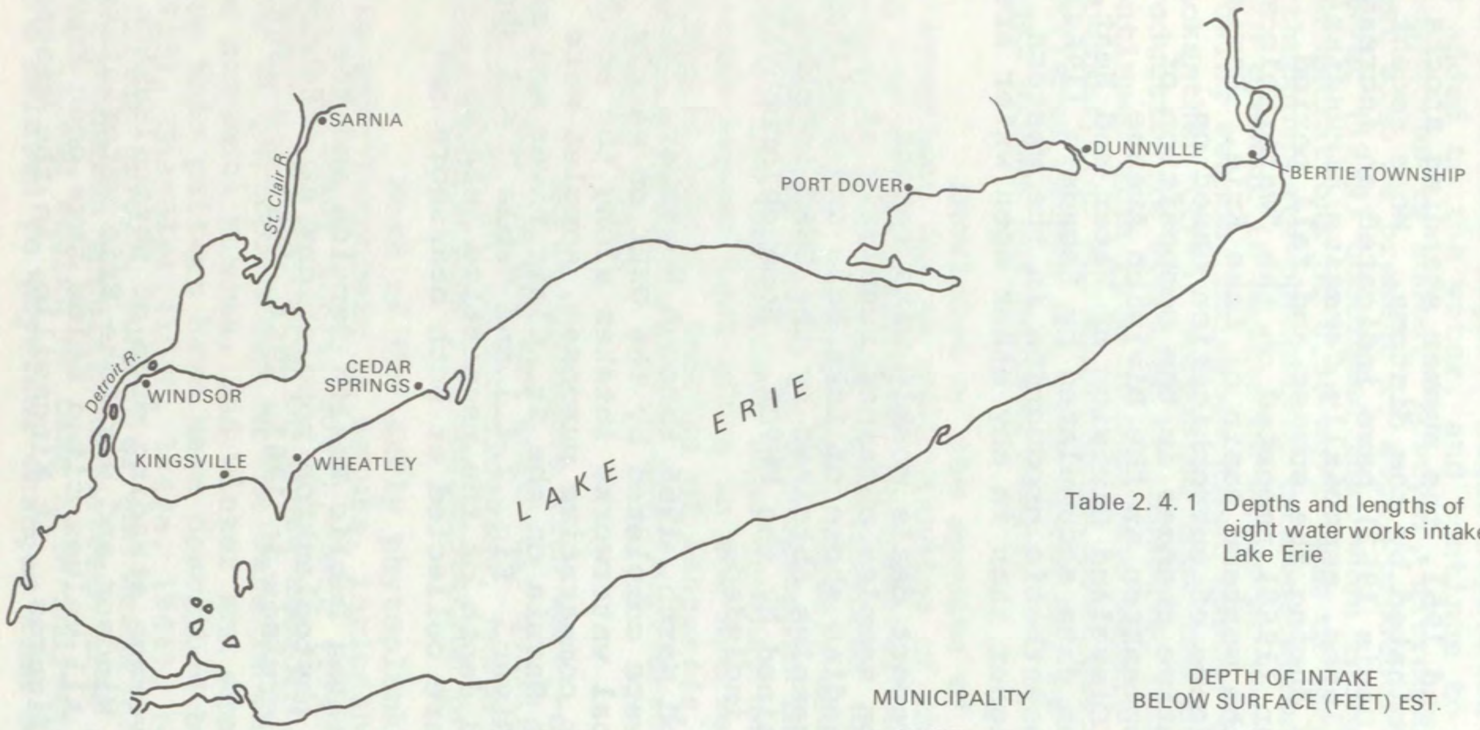


Table 2. 4. 1 Depths and lengths of eight waterworks intakes, Lake Erie

MUNICIPALITY	DEPTH OF INTAKE BELOW SURFACE (FEET) EST.	LENGTH OF INTAKE (FEET)
SARNIA	35	372
WINDSOR	15 and 20	1650 and 1250
KINGSVILLE	10	1500
WHEATLEY	14	2350
CEDAR SPRINGS	30	2461
PORT DOVER	12	1500
DUNNVILLE	21	1650
BERTIE TOWNSHIP	12	1800

Fig. 2. 4. 1 Location of eight municipal waterworks sampled for phytoplankton, 1966 - 1967.

basin, the average for 1966 was 2,100 areal standard units per ml (asu/ml); for 1967, 5,200 asu/ml. In the western part of the central basin, samples taken at Wheatley were characterized by phytoplankton averages of 1,200 and 1,000 asu/ml for 1966 and 1967, respectively. Yearly means at Cedar Springs located in the mid-central basin were 420 and 670 asu/ml. In contrast, low phytoplankton averages characterized the standing crops of the three stations in the eastern basin. The yearly averages at Port Dover were 520 and 360 asu/ml; while corresponding values at the Bertie Township Water Filtration Plant were 220 and 250 asu/ml. At Dunnville, slightly higher averages of 670 asu/ml in 1966 and 560 asu/ml in 1967 were recorded. At Sarnia, phytoplankton crops averaged 540 and 434 asu/ml, and at Windsor values were 720 and 790 asu/ml indicating a progressive increase in productivity in the St. Clair - Detroit River system.

Analyses of 149 samples collected during the summer of 1967 indicated a pattern of phytoplankton development similar to that at the inshore locations. An average of 1,400 asu/ml was obtained from 33 samples at 13 stations in the western basin. Eighty-two samples from 22 locations in the central basin averaged 410 asu/ml. In contrast, an average of 270 asu/ml was obtained for 34 samples from 10 stations in the eastern basin of Lake Erie. The above data indicate that the yearly average standing crop of phytoplankton decreased in order from the western to the eastern basins.

The seasonal bimodal pattern of plankton development in large lakes has been documented by Chandler (1940, 1942, 1944), Davis (1954a, 1962) and Pennak (1946). Pennak described the pattern as having a "... large spring pulse, a decreased population during the summer, a second, less pronounced, pulse in the autumn, and a very small population during the winter". A pulse is any population which is at least twice as great as the mean annual population (Pennak, 1946). Fig. 2.4.2 depicts these seasonal phytoplankton patterns for the samples taken from eight municipal intakes. With some variations, the classical pattern characterized the phytoplankton development at the three municipalities in the eastern basin and at Sarnia and Windsor. At Kingsville, the 1966 fall maximum extended into the spring of 1967 so that the 1966 to 1967 winter minimum failed to develop. Similarly, the 1967 spring and fall maxima all but obscured the summer minimum. At Wheatley and Cedar Springs, definite spring maxima and winter minima did not materialize and high levels of algae prevailed during the summer months.

Fig. 2.4.3 summarizes the quantitative and qualitative aspects of the monthly phytoplankton crops at each municipality.

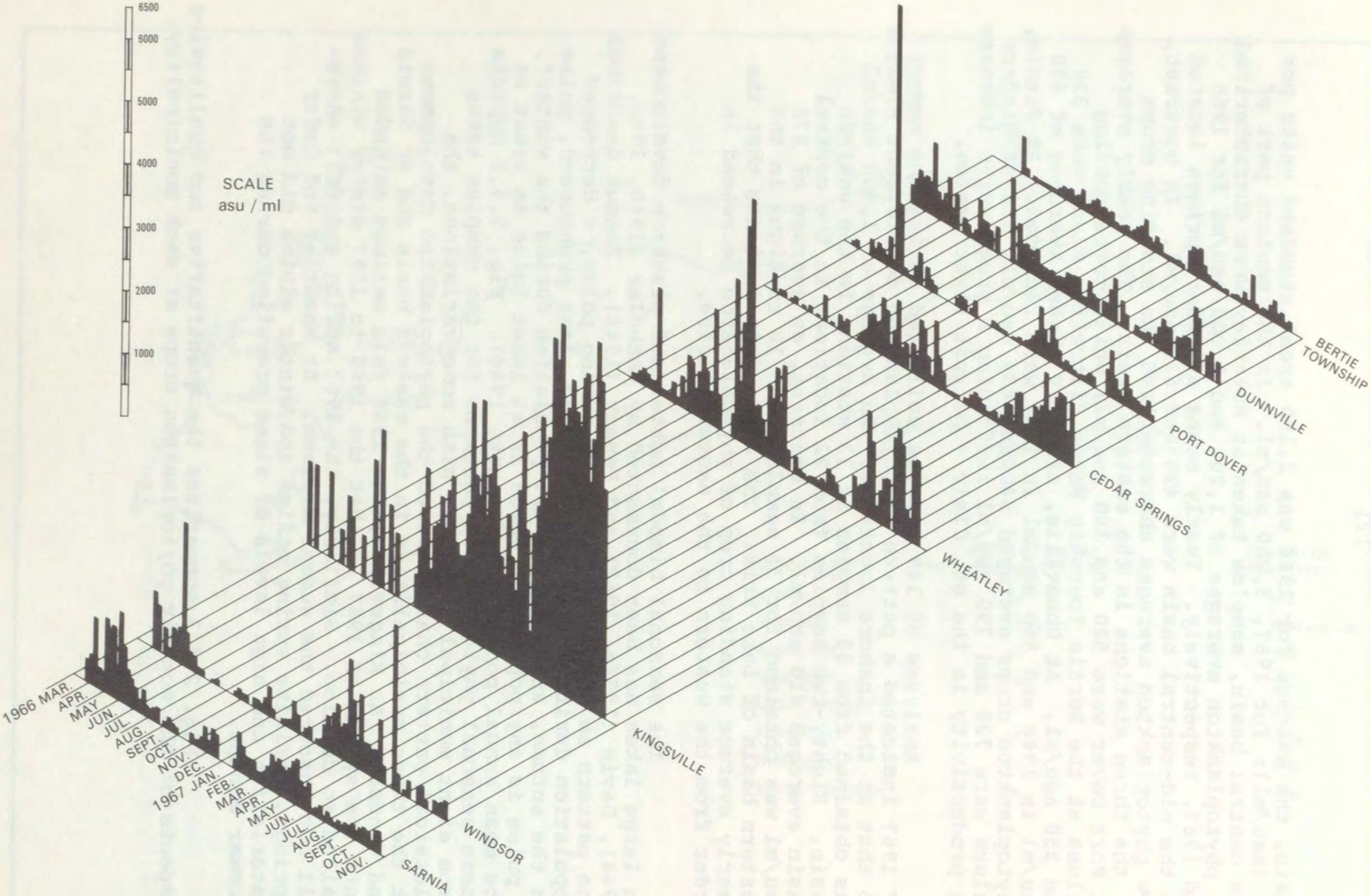
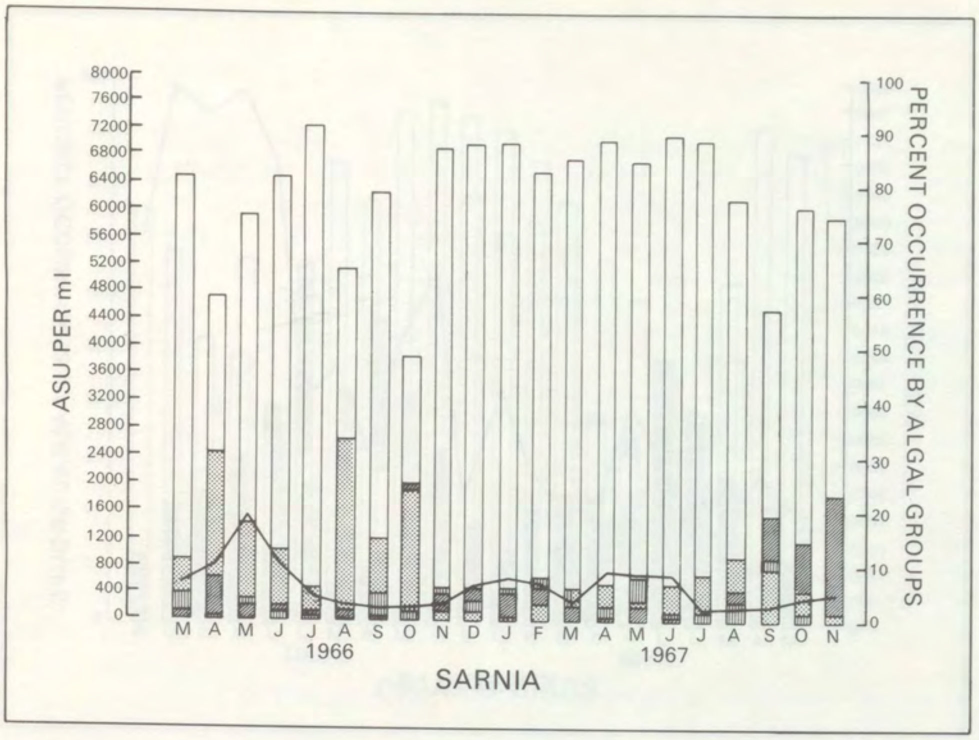


Fig. 2.4.2 Phytoplankton summary for Canadian waterworks samples (asu/ml).



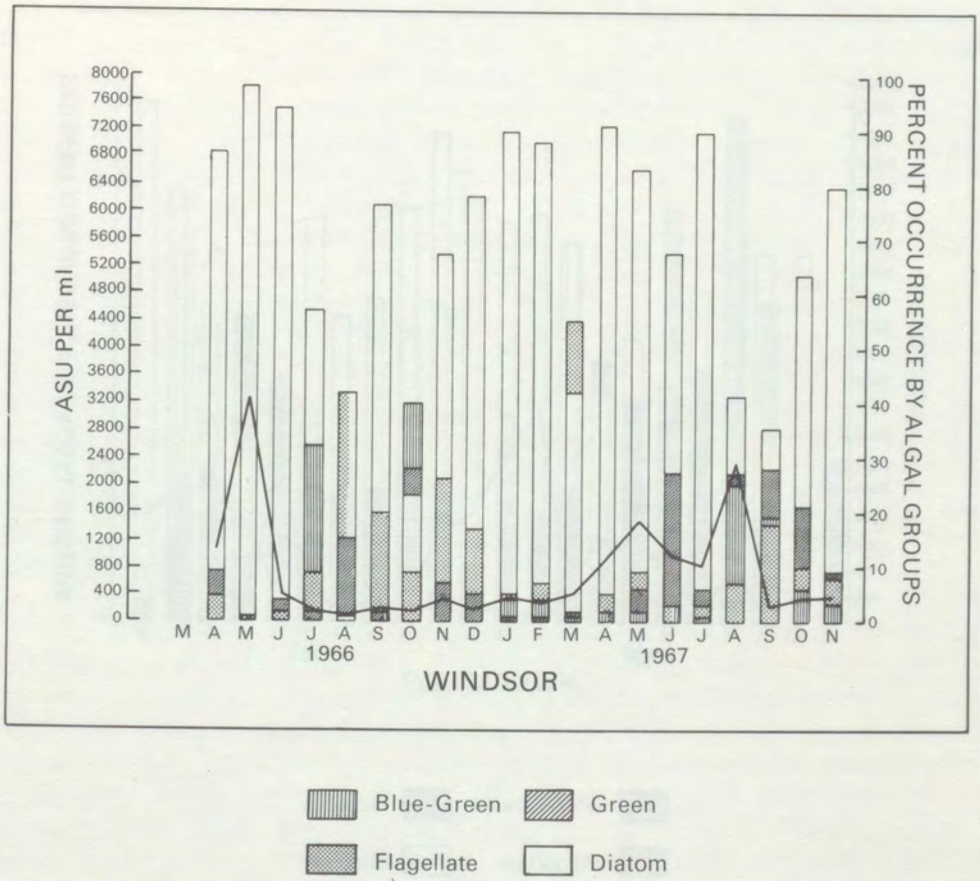
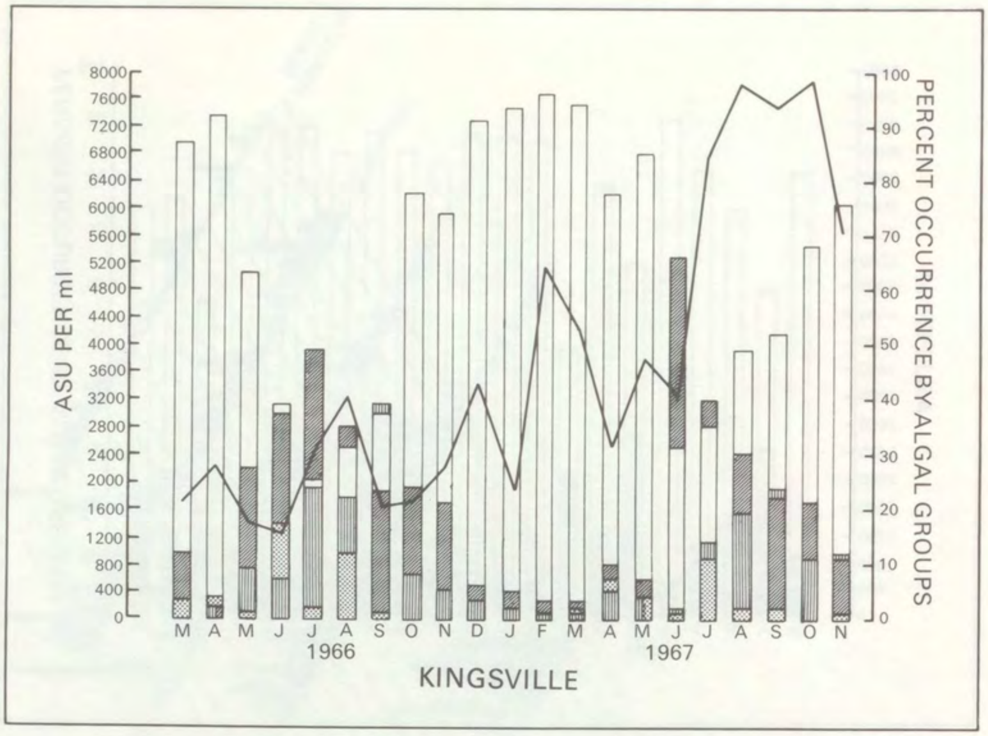


Fig. 2. 4. 3 Phytoplankton summary monthly averages (line graph - asu/ml: bar graph - percent occurrence).



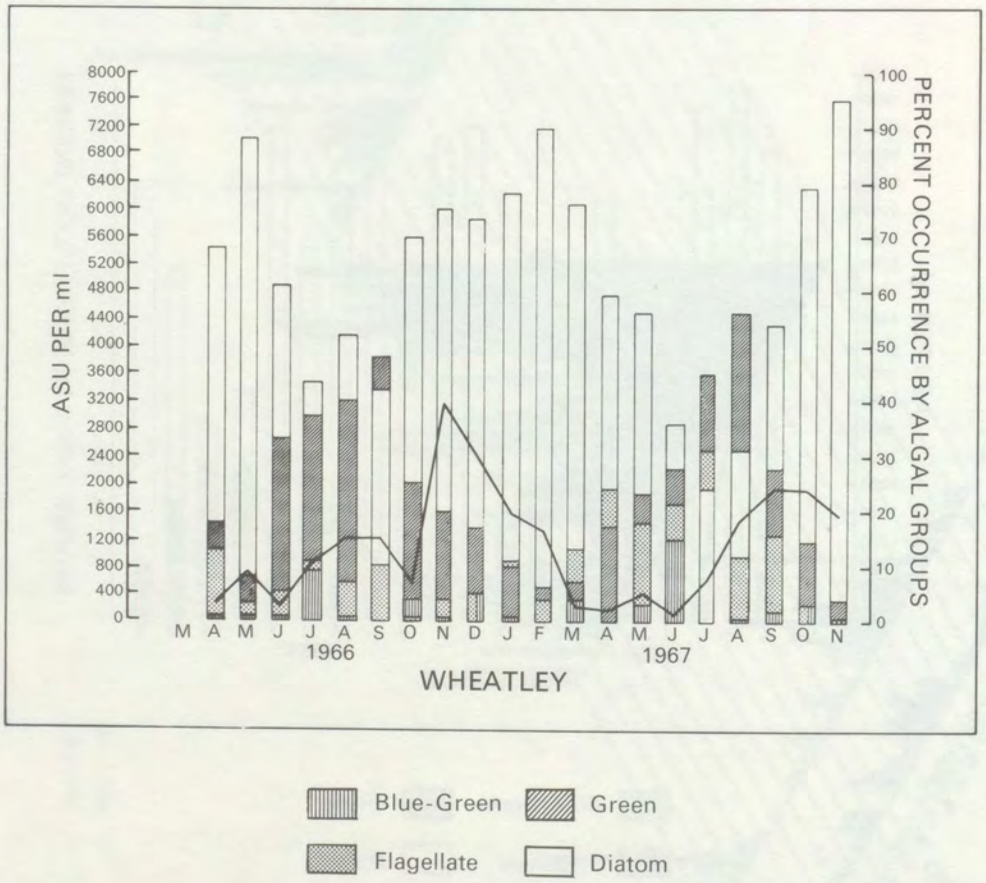
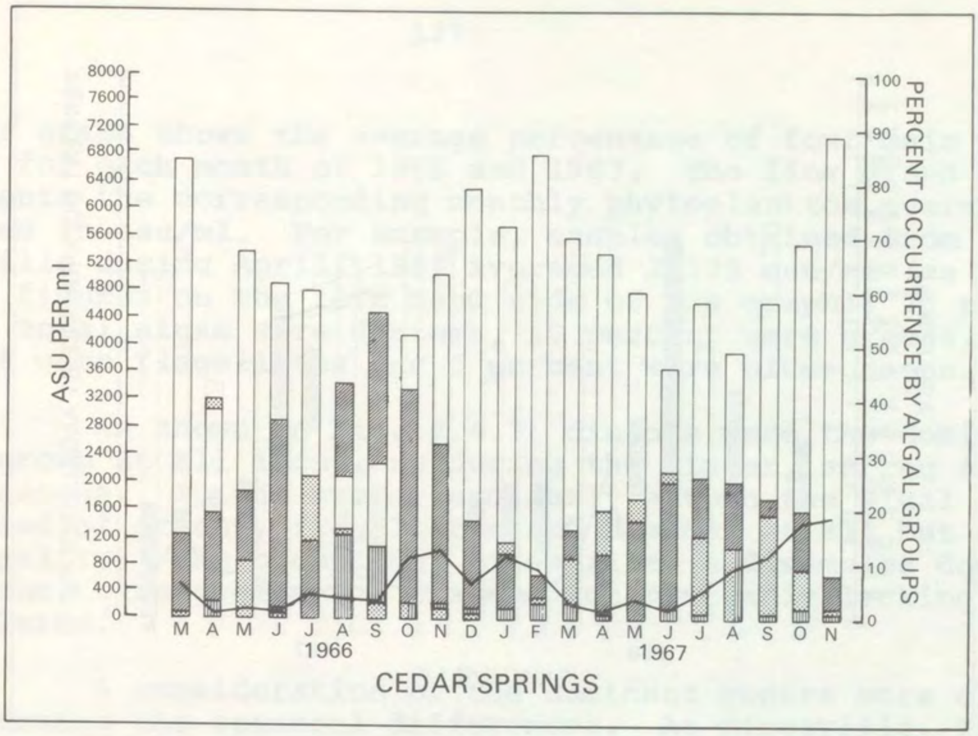
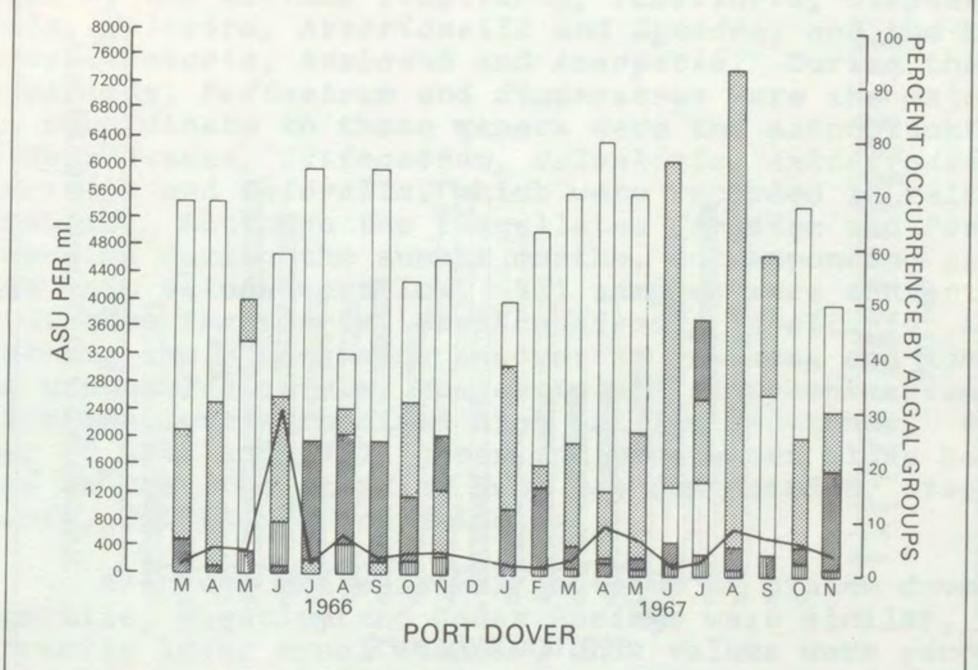


Fig. 2.4.3 cont'd





Blue-Green Green

Flagellate Diatom

Fig. 2.4.3 cont'd

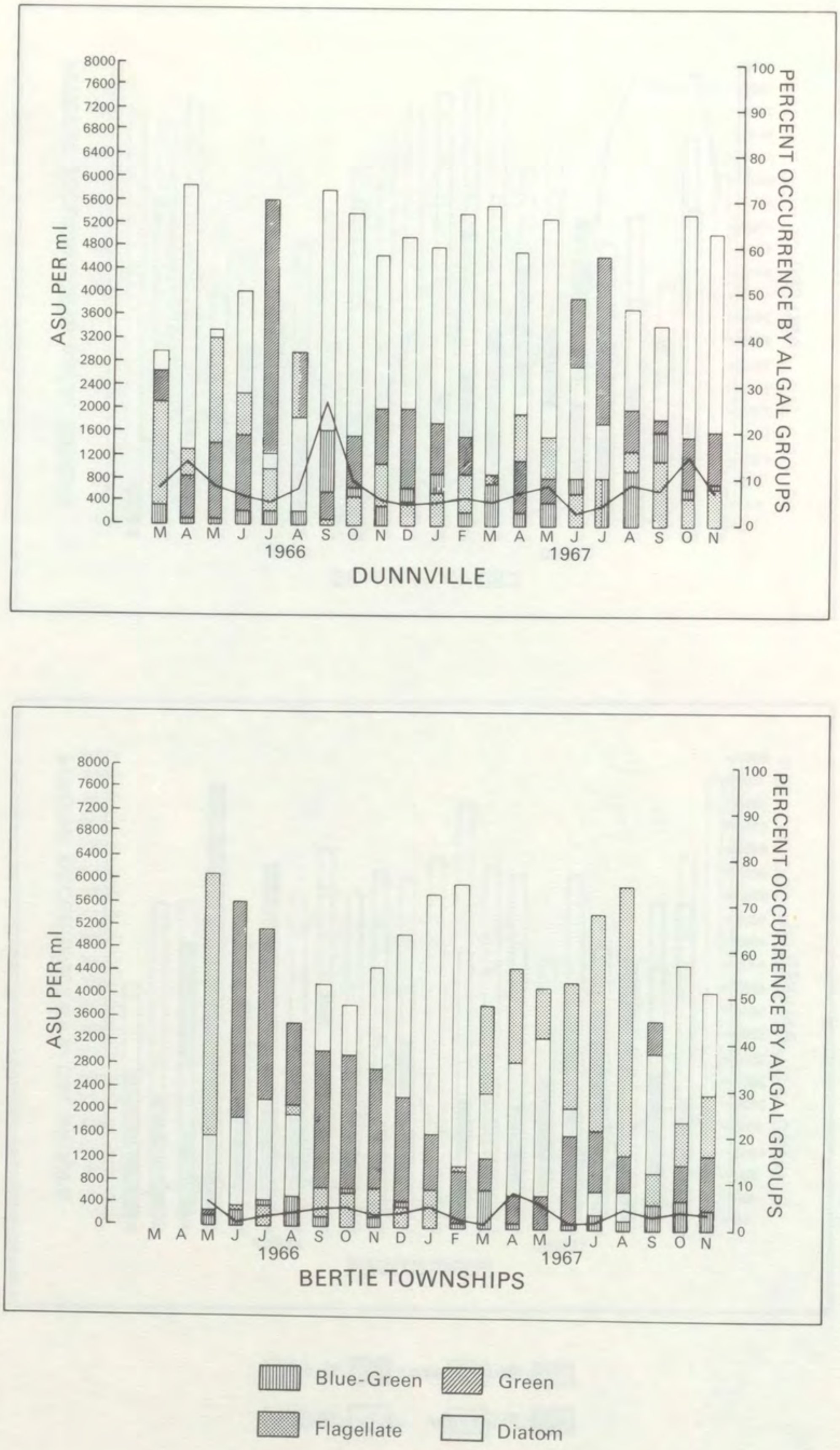


Fig. 2.4.3 cont'd

The bar graph shows the average percentage of four main algal groups for each month of 1966 and 1967. The line graph represents the corresponding monthly phytoplankton averages measured in asu/ml. For example, samples obtained from Kingsville during April, 1967 averaged 2,525 asu/ml (as indicated by the figures on the left hand side of the graph); 78 percent of the total algae were diatoms, 10 percent were greens, 7 percent were flagellates and 5 percent were blue-greens.

As shown in Fig. 2.4.3. diatoms were the dominant algal group at all locations during the winter, spring and fall seasons. In the summer and early autumn the algal flora consisted of greens, flagellates and diatoms at all but one municipality. The exception, Kingsville, had samples dominated by greens, blue-greens and diatoms but virtually lacking in flagellates.

A consideration of the dominant genera more clearly demonstrates the seasonal differences. At Kingsville, the 1966 and 1967 vernal maxima consisted of the diatoms *Stephanodiscus*, *Melosira*, *Fragilaria*, *Asterionella*, *Tabellaria* and *Diatoma*. The summer standing crops of phytoplankton for both years were dominated by the diatoms *Fragilaria*, *Tabellaria*, *Stephanodiscus*, *Surirella*, *Melosira*, *Asterionella* and *Synedra*, and the blue-greens *Oscillatoria*, *Anabaena* and *Anacystis*. During these summer periods, *Pediastrum* and *Staurastrum* were the major green algae. Subordinate to these genera were the nannoplanktonic greens *Scenedesmus*, *Actinastrum*, *Golenkinia*, *Ankistrodesmus*, *Kirchneriella* and *Chlorella*, which were recorded in relatively high numbers. Although the flagellates *Ceratium* and *Peridinium* were reported during the summer months, corresponding areal standard unit values were low. All samples were characterized by the diatoms *Fragilaria*, *Stephanodiscus*, *Tabellaria*, *Melosira* and *Diatoma*; the blue-greens *Anacystis*, *Anabaena* and *Agmenellum*; and the greens *Pediastrum*, *Mougeotia* and *Dictyosphaerium*. The nannoplankton levels remained high until mid-October. By mid-November of 1966 and 1967, green and blue-green algae had declined so that the standing crop was dominated by *Stephanodiscus*, *Fragilaria*, *Tabellaria* and *Melosira*.

Although the seasonal patterns of diatom development at Kingsville, Wheatley and Cedar Springs were similar, significantly lower areal standard unit values were recorded at the latter two municipalities. At Cedar Springs and Wheatley, summer and fall levels of blue-green algae were negligible. Samples collected during the summer and fall months at these locations contained moderated number of the flagellates *Peridinium*, *Ceratium*, *Dinobryon*, *Cryptomonas* and *Trachelomonas* and the chlorophycean forms *Pediastrum* and *Staurastrum*. In contrast to the high nannoplanktonic values recorded at Kingsville the summer and fall samples from Wheatley and Cedar Springs were characterized by low numbers of *Scenedesmus*, *Ankistrodesmus*, *Schroederia*, *Lagerheimia* and *Micractinium*.

At Port Dover, Dunnville and Bertie Township the major genera reported during the winter and spring months were the diatoms *Stephanodiscus*, *Melosira*, *Tabellaria*, *Fragilaria* and *Asterionella*, and the flagellates *Peridinium*, and *Dinobryon*. With the exception of the presence of *Aphanizomenon* during July and August of 1966 at Dunnville, blue-green populations failed to develop. During the summer and fall months, the flagellates *Ceratium*, *Cryptomonas*, *Dinobryon* and *Peridinium* and the greens *Pediastrum* and *Staurastrum* were co-dominant along with approximately equal numbers of the diatoms *Fragilaria*, *Tabellaria* and *Asterionella*.

Results of the FWPCA phytoplankton analyses for spring, summer and fall cruises in 1963 and 1964 and spring, summer, fall and winter cruises during the 1967 to 1968 period were averaged for all stations and separated according to basins and seasons. Table 2.4.2 summarizes those data. Generally, offshore phytoplankton populations decreased from the western to the central to the eastern basins in agreement with results from nearshore stations.

Spring pulses in the western basin in 1963 and 1967 consisted primarily of diatoms (*Cyclotella - Stephanodiscus*). Low spring populations were noted in the central and eastern basins. In the summer months, lower aggregate values were recorded. During the summer cruise of 1963, the flora consisted mainly of diatoms in the central and eastern basins; and green and blue-green diatoms in the western basin. The fall populations for 1964 reflected the extensive blue-green phytoplankton bloom that was reported for western Lake Erie in September of that year (Casper, 1965). The bloom, covering approximately 800 square miles, consisted primarily of *Oscillatoria sp.*, *Aphanizomenon holsaticum*, *Anacystis cyanea*, *Anabaena circinalis*, and *Carteria sp*. Average surface concentrations were 16,000 counts per millilitre with a maximum of 56,000 counts per millilitre. The autumnal increases in 1967 in the western basin were characterized by diatoms, greens and blue-greens, while representatives of diatoms and the greens dominated in the central and eastern basin locations.

Studies by Davis (1964, 1965), Bradshaw (1964) and Verduin (1964) on long-term changes in plankton populations demonstrated an accelerated rate of eutrophication of Lake Erie during recent years. Davis (1964) summarized plankton

Table 2.4.2 Lake Erie midlake phytoplankton populations per millilitre, 1963 - 1964 and 1967 - 1968.

Type of algae	Season	Basin Western	Central	Eastern
1963 to 1964				
Blue-green	Spring	380	650	290
Diatom	Spring	1,400	520	290
Blue-green	Fall	10,500	880	120
Diatom	Fall	320	130	65
1967 to 1968				
Diatom	Spring	1,900	240	500
Blue-green	Spring	91	91	50
Green	Spring	150	81	35
Flagellate	Spring	47	51	31
Diatom	Summer	470	45	35
Blue-green	Summer	210	100	230
Green	Summer	270	140	86
Flagellate	Summer	52	32	29
Diatom	Fall	1,400	280	100
Blue-green	Fall	230	12	7
Green	Fall	960	180	63
Flagellate	Fall	36	28	10
Diatom	Winter	510	390*	-
Blue-green	Winter	11	20*	-
Green	Winter	61	180*	-
Flagellate	Winter	16	58*	-

*Three (3) station average
-No data available

data accumulated by the Cleveland Division Avenue Filtration Plant between 1919 and 1963. Although year-to-year variations were large, a definite long-term increase in plankton populations was apparent as indicated in Fig. 2.4.4. Davis' data showed that plankton counts increased from a yearly average of 200 to 400 cells per millilitre between 1920 and 1930 to a current average of 1,500 to 2,300 cells per millilitre. This represents an increase of between 500 and 700 percent in the Cleveland area. As previously cited, Davis attributed these changes to rapid eutrophication. Owing to the relatively short sampling periods reported by the OWRC (1966 to 1967) and the FWPCA (1963 to 1964 and 1967 to 1968), it was impossible to associate fluctuations in phytoplankton levels with trends in water quality. However, differences in algal levels throughout the lake indicated decreasing eutrophy from the western through the central to the eastern basins.

Relatively high algal levels characterized the samples collected from the Dunnville and Windsor Water Filtration Plants. The levels at Dunnville reflected the impact of the nutrient-enriched Grand River (Ontario) Watershed. At Windsor, the increased phytoplankton levels as compared with those at Sarnia were attributed, in part, to the input of agricultural, industrial and domestic wastes into Lake St. Clair, and the Detroit River.

With regard to the seasonal pattern of plankton development, Davis (1964) reported that between 1919 and 1963 there was an increase in the intensity and duration of the spring and fall maxima as well as a failure of the summer and winter minima to materialize. This suggested a rapid enrichment of the Lake Erie waters. Evidence of these changes is clearly depicted in Fig. 2.4.4. As described in the nearshore results, a similar pattern characterized the standing crop of phytoplankton at Kingsville for 1966 to 1967, thus indicating the eutrophic condition of the western basin of Lake Erie.

In Lake Erie, the algal forms varied depending on location and season. At Kingsville, diatoms were dominant during all seasons and few flagellates were recorded. Although diatoms predominated during the summer and fall periods, significant numbers of green and blue-green forms were also present then. During this study, summer and fall blue-green populations were not high enough to constitute "water-bloom" conditions such as described by Tiffany (1958) and Casper (1965).

At Wheatley, Cedar Springs, Port Dover, Dunnville and Bertie Township, flagellates constituted a major portion

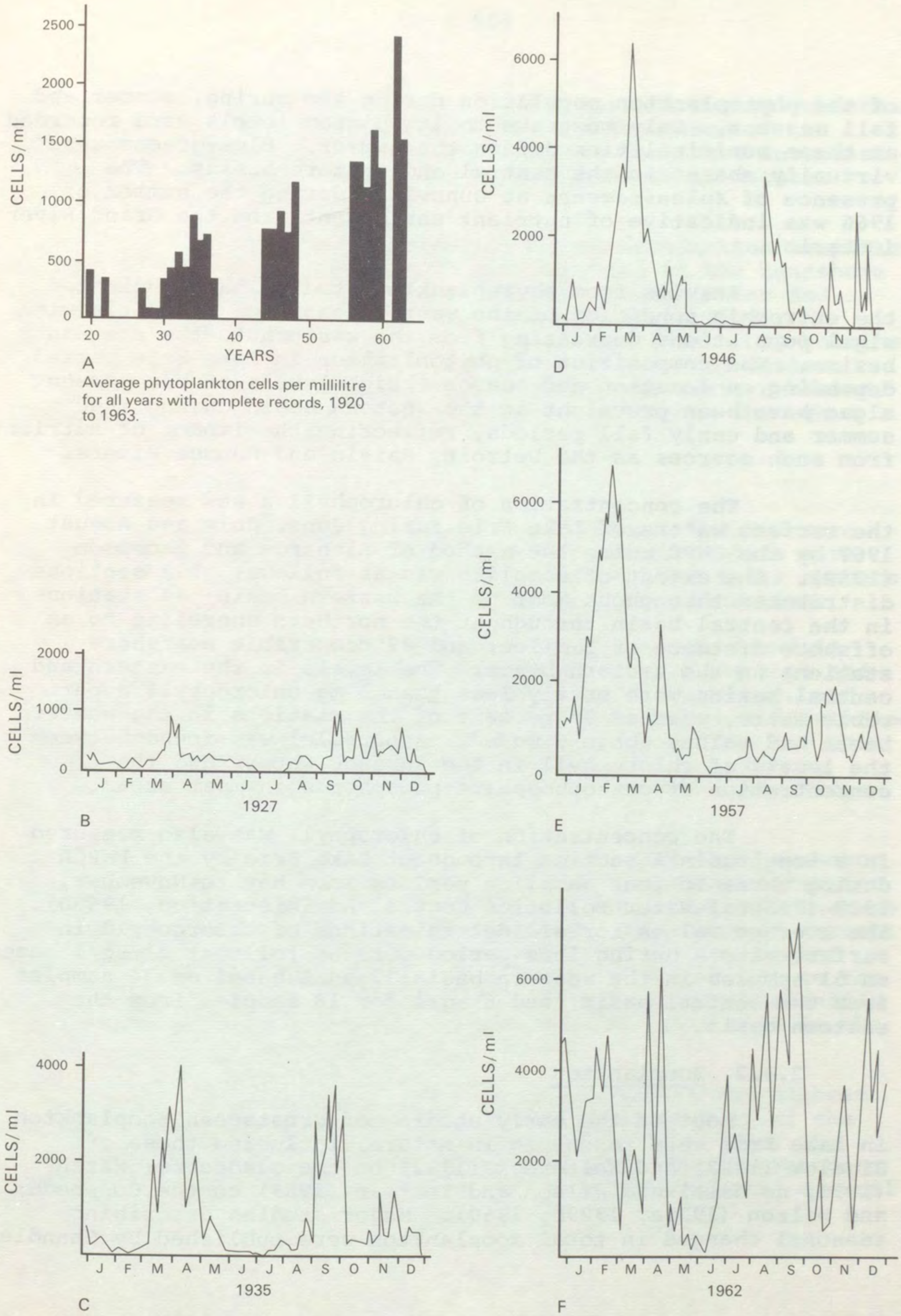


Fig. 2.4.4 Phytoplankton populations, (cells per millilitre) at the Cleveland Avenue Filtration Plant 1919 to 1962 (Redrawn from Davis 1964).

of the phytoplankton population during the spring, summer and fall seasons. Only moderate to low diatom levels were recorded at these municipalities during the summer. Blue-greens were virtually absent in the central and eastern basins. The presence of *Aphanizomenon* at Dunnville during the summer of 1966 was indicative of nutrient enrichment from the Grand River (Ontario).

Results from phytoplankton studies have indicated the eutrophic condition of the western basin of Lake Erie with algal populations decreasing from the western to the eastern basins. The composition of phytoplankton in Lake Erie varied, depending on location and season. High levels of blue-green algae have been prevalent in the western basin during the summer and early fall periods, reflecting the impact of nutrients from such sources as the Detroit, Raisin and Maumee Rivers.

The concentration of chlorophyll a was measured in the surface waters of Lake Erie during June, July and August 1967 by the OWRC using the method of Richards and Thompson (1952). The extent of sampling was as follows: 122 stations distributed throughout most of the western basin; 44 stations in the central basin throughout the northern shoreline to an offshore distance of 5 miles; and 89 comparable nearshore stations in the eastern basin. The levels in the eastern and central basins were mostly less than 5 mg chlorophyll a per cubic metre, whereas 74 percent of the stations in the western basin had values above 5 mg/m^3. A parallel was found between the levels of chlorophyll in the surface waters and the concentration of orthophosphate-phosphorus in most areas.

The concentration of chlorophyll was also measured in a longitudinal section throughout Lake Erie by the FWPCA during three to four sampling periods from May to November, 1967 (Federal Water Pollution Control Administration, 1968b). The average values for all determinations of chlorophyll in surface waters during this period were as follows: 21 μg/l based on 51 samples in the western basin; 7 μg/l based on 34 samples from the central basin; and 6 μg/l for 18 samples from the eastern basin.

2.4.2 Zooplankton

Most of the early studies of crustacean zooplankton in Lake Erie were taxonomic in nature, including those of Bigelow (1922) and Woltereck (1932) on the Cladocera; Marsh (1895, no date) and Wilson and Yeatman (1959) on the Copepoda; and Wilson (1929a, 1929b, 1960). Major studies describing seasonal changes in total zooplankton were published by Chandler

(1940) and Davis (1954b, 1962). In the western basin, Hubschman (1960) followed the daily fluctuations in abundance of the planktonic crustaceans and Bradshaw (1964) described increases in the maximum numbers of copepods and cladocerans between 1939 and 1959.

This report outlines results of zooplankton sampling by OWRC in the western basin of Lake Erie and in the nearshore waters of the central and eastern basins. Between May and September, 1967, 11 stations were sampled regularly for planktonic crustaceans using a Wisconsin net (Number 20 bolting cloth mesh). Of the 11 stations, three were in the eastern basin and four were in each of the central and western basins. At all stations, the plankton net was slowly drawn through a 7 metre vertical column of water.

Results

The two dominant groups of Crustacea sampled were the Copepoda and Cladocera. Although other crustaceans were identified including the Ostracoda and Amphipoda, their numbers were extremely low and were not considered representative.

Two suborders of limnetic copepods were found in the lake. The Cyclopoida was represented by *Cyclops spp.* and *Mesocyclops edax*. The Calonoida included *Diaptomus spp.* and *Eurytemora affinis*. A single *Epischura lacustris* was identified from a station in the western basin of the lake. The two main cladoceran forms were *Daphnia spp.* and *Bosmina sp.* Other cladocerans included *Chydorus sphaericus*, *Leptodora kindtii*, *Holopedium sp.* and *Ceriodaphnia sp.*

Table 2.4.3 outlines the maximum and average number of Copepoda (Cyclopoida and Calanoida) and Cladocera taken in the three major basins of Lake Erie. As indicated, the average standing crop of cyclopoids in the eastern basin was 25 percent higher than that in the central basin and 43 percent higher than that recorded from the western basin. In contrast to the cyclopoids, low numbers of calanoids were reported. Calanoids were four times more abundant in the western basin than in the central and eastern basins.

Cladocerans were lowest in the central and highest in the western basin where they formed the major part of the crustacean population. At the western end of the lake, the numbers of cladocerans were more than double the corresponding maximum and average values recorded for the eastern and central basins.

Table 2.4.4 summarizes the maximum and average numbers of planktonic crustacea in the three basins of Lake Erie. *Cyclops spp.*, the dominant cyclopod, was represented by *Cyclops bicuspidatus* and *Cyclops vernalis*. These species attained maximum numbers between the middle of June and the first week in July. Although the highest count reported was from the central basin (217,000/m^3), average numbers indicated an overall decline from the eastern to the western ends of the lake. Low numbers of *Mesocyclops edax* were reported from all basins between April and the end of August.

Calanoid copepods were represented by several species of the genus *Diaptomus*, including *Diaptomus oregonensis*, *Diaptomus siciloides*, *Diaptomus minutus*, *Diaptomus ashlandi*, *Diaptomus sicilis* and *Diaptomus reighardi*, and the brackish water form *Eurytemora affinis*. Maximum numbers of diaptomids were found early in July and in mid-August at stations in the eastern and central basins. In the western basin a maximum of 15,000/m^3 for diaptomids occurred earlier in the year (mid-June). *Eurytemora affinis* was obtained at stations in the eastern and western basins, being more abundant in the latter.

The dominant cladocerans were *Daphnia spp.* and *Bosmina sp.* Throughout the lake, two periods of cladoceran development were apparent, one in the latter half of June, and the second about mid-August. Daphnids dominated during the late spring while smaller cladocerans (mainly *Bosmina sp.*) were proportionately more abundant during the August pulse. During May and June, low numbers of *Chydorus sphaericus* were reported at stations in the central basin and in the western basin. In August, this species reached a high of 1,600/m^3 at one station in the extreme west end of the lake. *Leptodora kindtii*, although not sampled quantitatively, was taken most frequently at stations in eastern Lake Erie. Small numbers of *Ceriodaphnia sp.* and *Holopedium sp.* were obtained from stations in the eastern basin and central basin.

Between September 1938 and September 1939, Chandler (1940) studied the phytoplankton and zooplankton from a 1,000 acre area in the Bass Island region of western Lake Erie. From October 1948 to October 1949, Bradshaw (1964) and Verduin (1964) collected samples at one location on the western edge of that area. Between June 30 and August 21, 1959, Hubschman (1960) collected daily zooplankton samples at one station between Gibraltar and Middle Bass Islands. Bradshaw (1964), utilizing information from all three studies, reported that a considerable increase had taken place in crustacean zooplankton in western Lake Erie. In the western basin, maximum numbers of Copepoda increased from 70,000/m^3 in June of 1939 to 97,000/m^3

Table 2.4.3 Counts (expressed in numbers of animals per cubic metre) of Cyclopoida, Calanoida and Cladocera for Lake Erie, 1967. Values for the Cyclopoida and Calanoida include juvenile forms (Copepoda nauplii are not included).

	Eastern basin		Central basin		Western basin	
	maximum	average	maximum	average	maximum	average
Cyclopoida	250,000	61,000	220,000	47,000	110,000	35,000
Calanoida	6,900	1,200	12,000	1,300	29,000	4,400
Cladocera	120,000	35,000	68,000	30,000	340,000	71,000

Table 2.4.4 Planktonic crustaceans (expressed in numbers of animals per cubic metre) for Lake Erie, 1967 (Copepoda nauplii are not included).

	Eastern basin		Central basin		Western basin	
	maximum	average	maximum	average	maximum	average
Cyclopoida						
Mesocyclops edax	1,200	130	1,600	210	950	140
Cyclops spp.	201,000	51,000	220,000	49,000	112,000	27,000
Cyclopoid stages	49,000	10,000	48,000	4,900	32,000	7,100
Calanoida						
Diaptomus spp.	4,700	840	6,300	790	15,000	2,100
Eurytemora affinis	950	90	0	0	3,300	570
Calanoid stages	2,200	270	5,400	470	12,000	1,700
Cladocera						
Bosmina sp.	103,000	18,000	40,000	11,000	170,000	28,000
Daphnia spp.	55,000	17,000	48,000	11,000	240,000	35,000
Leptodora kindtii	5,700	430	25	1	630	87
Ceriodaphnia sp.	950	70	320	16	0	0
Holopedium sp.	320	20	630	32	0	0
Chydorus sphaericus	0	0	320	69	1,600	200

in July of 1949 and to 165,000/m^3 in July, 1959. A copepod maximum of 126,201/m^3 was reported on June 12, 1967 at a station just north of the Bass Island region. Although this was lower than Hubschman's maximum, it was 23 percent higher than the maximum recorded by Bradshaw (1964) and Verduin (1964) in 1949. In the eastern basin, results from the present study indicated that numbers of Copepoda reached a maximum of 252,000/m^3 at a station located near the mouth of Long Point Bay. In the central basin in 1951, Davis (1954b) found a copepod maximum of 23,000/m^3. In mid-June of 1952, the same author (Davis, 1962) reported a maximum of 74,000/m^3. Both values are considerably lower than the 219,000/m^3 recorded during the present study.

Bradshaw (1964) reported that cladocerans increased in the western basin from a maximum of 16,000/m^3 in June 1939 to 49,000/m^3 in June 1949 to 202,000/m^3 in June of 1959. A high of 344,000/m^3 was encountered during the current study north of the Bass Island region on June 12, 1967. During the summer of 1967, numbers of Cladocera exceeded the 1948 to 1949 maximum in 50 percent of the samples collected from the western basin.

Chandler (1940) described the seasonal distribution of copepods in the western basin of the lake. Five species of *Cyclops*, five of *Diaptomus*, and *Limnocalanus macrurus*, *Epischura lacustris* and *Canthocamptus staphylinoides* were found. With the exception of *Limnocalanus macrurus*, similar species were recorded during Bradshaw and Verduin's 1948 to 1949 survey. In the present study, *Limnocalanus macrurus* and *Canthocamptus staphylinoides* were not recorded. *Eurytemora affinis* was first encountered by Engel (1962) in western Lake Erie and was found recently in the eastern and western basins. Bradshaw (1964) considered this species to be indicative of a definite qualitative change in western Lake Erie. Wright (1955) suggested that the occurrence of *Diaptomus siciloides* in Lake Erie in 1929 and 1930 was incidental, but Chandler (1940) found this species to be abundant in autumn and Jahoda (1948) reported it during the summer and fall months in the western basin. Finally Davis (1962) in 1956 and 1957 recorded *D. siciloides* in the central basin and found it to be one of the two most common calanoids in all three basins of the lake. Davis (1966a) concluded, "this development is perhaps significant as an indication of certain fundamental changes in the character of the lake itself, for this species is known primarily as an inhabitant of ponds and of warm eutrophic waters."

In all studies, the genus *Daphinia* has been important because of its numbers and biomass. Chandler (1940) reported *Daphnia longispina* (probably *Daphnia galeata mendotae*), *Daphnia* *retrocurva* and *Daphnia pulex* as the major forms. In 1939, *Daphnia longispina* reached a late spring maximum of 9,000/m^3. *Daphnia retrocurva* was reported coincidently with *Daphnia longispina*, but never exceeded 4,000/m^3. In contrast *Daphnia retrocurva* was twice as abundant during the 1948 to 1949 survey, reaching maxima of 46,000/m^3 and 20,000/m^3 in June and September, respectively. Also, *Daphnia longispina* increased to an August maximum of 11,000/m^3 and a September maximum of 20,000/m^3. Since Hubschman (1960) treated the cladocerans as a group, it is impossible to relate the aforementioned changes to those of his 1959 study. However, Hubschman found "the largest group of Cladocera was of the genus *Daphnia*, but *Bosmina*, *Chydorus* and *Diaphanosoma* showed periodic pulsations during the summer." Davis (1954b, 1962) indicated the presence of similar populations in the western basin of the lake. Generally, daphnids were the most abundant cladocerans found during the summer of 1967.

Chandler (1940) reported that *Bosmina longirostris* reached a maximum of 10,000/m^3 in the western basin in the fall of 1939. The maximum for this species during the 1948 to 1949 survey was 4,600/m^3. As mentioned previously, Hubschman (1960) reported periodic summer pulsations of *Bosmina*. Davis (1962) in a survey of the Cleveland Harbour area found that averages for *Bosmina* were 51,700/m^3 in November of 1956 and ranged from 35,600 to 85,700/m^3 during June of 1957. During the present study, averages for *Bosmina* were highest in the western basin, but were considerably lower than those reported by Davis.

From the 1938 to 1939 study *Chydorus sphaericus* was not reported but during the 1948 to 1949 survey "...was present from August to January with a September maximum of 3,690/m^3." Davis (1954b, 1962) encountered small numbers of this species in the central basin of the lake. In early August 1967, a maximum of 1,600/m^3 was reported from a station in the western basin.

Although rotifers were not examined in any of the recent studies, some published information is available. Davis (1968) found during the summer of 1967 that a greater variety of rotifers occurred in the western basin of Lake Erie than in the central and eastern basins. *Synchaeta stylata* and *Brachionus angularis* were common in the western basin, but were rare elsewhere. *Conochilus unicornis*, *Keratella cochlearis*, *Keratella quadrata*, *Kellicotia longispina*, and *Asplanchna sp.* occurred throughout the lake, but were most abundant in the western basin. On the other hand *Polyarthra vulgaris*, the most common rotifer, was least abundant in the western basin, much more common in the central basin and most abundant in the eastern basin. In general, *Polyarthra spp.* and *Keratella cochlearis* have been the most abundant species according to many authors (Burkholder, 1929; Ahlstrom, 1934; Chandler, 1940; Davis, 1954b, 1962; Williams, 1962; Fish, 1960). Other species that have been occasionally recorded as abundant are: *Chromogaster ovalis* (Burkholder, 1929); *Filinia longiseta* and *Brachionus angularis* (Ahlstrom, 1934); *Synchaeta spp.* (Ahlstrom, 1934; Chandler, 1940; Davis, 1954b) and *Conochilus unicornis* (Davis, 1966b).

Numbers of Copepoda in the eastern and central basins of Lake Erie exceeded corresponding values for the Cladocera while the opposite was the case in the western basin. The cyclopoids decreased from the eastern to the central to the western basin while high numbers of Calanoida and Cladocera were found in the western end of the lake.

The Copepoda were represented by *Mesocyclops edax*, *Eurytemora affinis*, two species of *Cyclops*, and five species of *Diaptomus*. In the western end of the lake the maximum number of Copepoda increased from $70,000/m^3$ in 1939 to $97,000/m^3$ in 1949 to $165,000/m^3$ in 1959. The maximum recorded for the western basin during the 1967 study was $126,000/m^3$. The recent occurrence of *Eurytemora affinis* is indicative of a definite qualitative change in calanoid populations. *Diaptomus siciloides*, which was reported as incidental in Lake Erie in 1929 and 1930 (Wright, 1955) is currently one of the two most abundant diaptomids (Davis, 1959, 1961).

The most abundant cladocerans were *Daphnia spp.* and *Bosmina spp.* Since 1939 a dramatic increase of cladoceran zooplankton has occurred. The "recent" occurrence of *Chydorus sphaericus* may be indicative of the changing nature of the lake.

2.4.3 Cladophora

One of the major problems in many areas of Lake Erie is that created by the filamentous green alga *Cladophora*. This alga grows extensively along the shorelines of the lower Great Lakes wherever there is a suitable rocky substrate (Fig. 2.4.5). Problems arise usually in July, at which time the long algal filaments break off during stormy weather, and accumulate on shore. Additional quantities of lesser magnitude may be deposited periodically throughout the remainder of the summer. Recreational and aesthetic values are seriously affected as the algae decompose, causing unsightly beaches and foul odours. Industries and municipalities have reported difficulties owing to *Cladophora* entering their water intakes. Commercial fishing operations have been seriously affected by

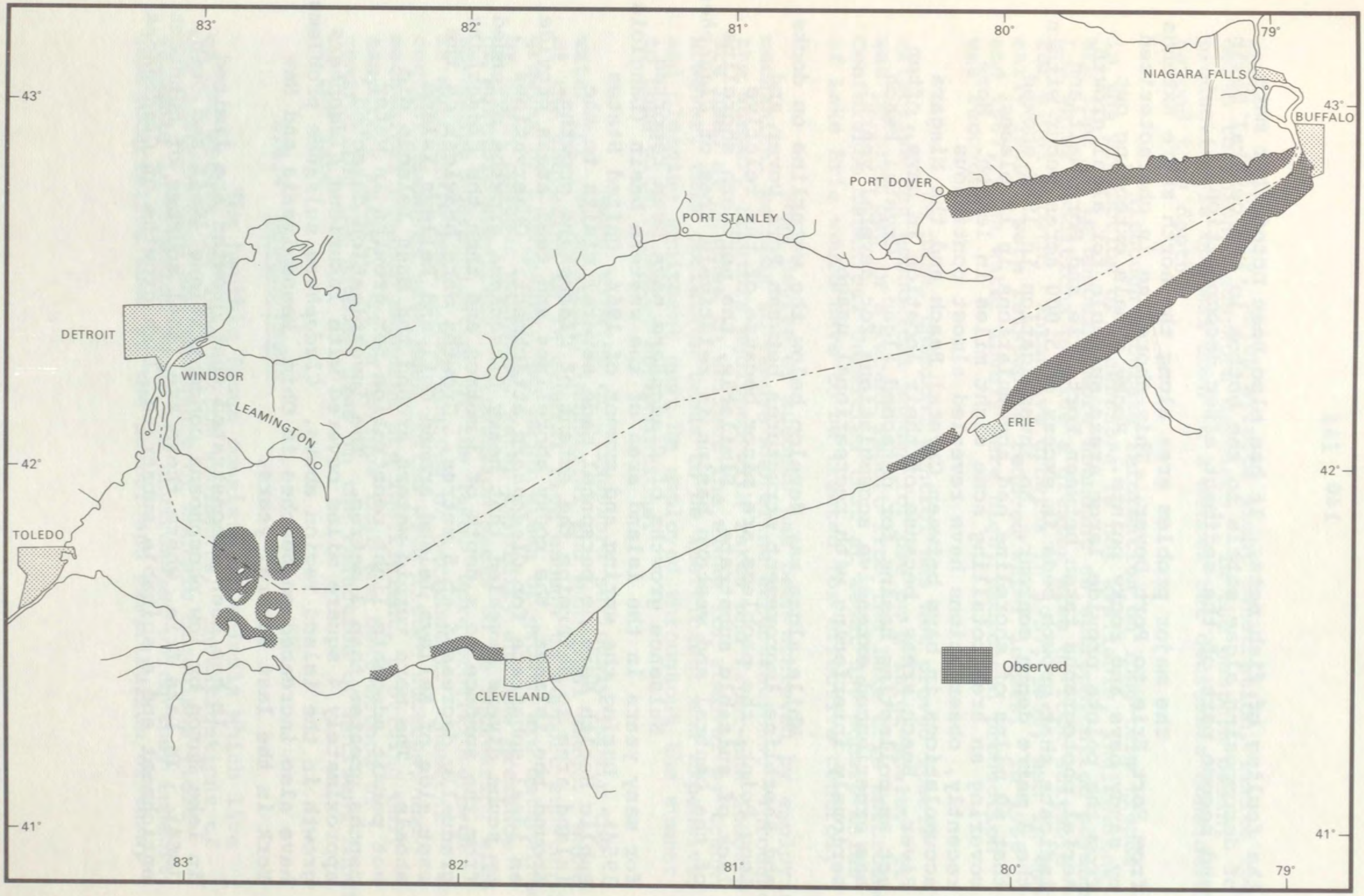


Fig. 2.4.5 Distribution of *Cladophora* in Lake Erie.

the fouling of fish nets. It has also been noted that mats of decomposing algae settle to the bottom in the central basin and become part of the sediment after decomposition.

The major problem area along the north shore extends from Fort Erie to Port Dover. This shoreline is characterized by sandy bays and rocky points. Rocky shoals extending out from the points provide large areas suitable for algal growth. Aerial photographs taken between Fort Erie and Port Maitland indicate that growth beds in excess of 5,000 acres occur within the 3 metre depth contour. An investigation in 1962 showed that 60 miles of shoreline had accumulations in 18 places, covering an area totalling some eight miles in length. More recently, observations have revealed almost continuous accumulations in bays between Crystal Beach and the Niagara River. Beach areas, because of their location in bays, often act as collecting basins for detached algae. Crystal Beach has experienced extensive accumulations for several years, seriously interfering with recreational usage.

While algae may develop below the waterline on docks and shoreline improvement structures between Port Dover and Long Point, the problems are minor because of the relative lack of suitable substrate. Similarly, the northern shoreline of the central and western basins is relatively free of *Cladophora*.

Nuisance growths of *Cladophora* have been reported for many years in the island area of the western basin (Langlois, 1954). During the spring and summer of 1964, United States Public Health Service personnel made several visits to the island area to determine the extent of *Cladophora* growths. Around the islands, the rocky shorelines and reef areas provide an ideal substrate for *Cladophora* attachment. Observations by scuba divers revealed that heavy *Cladophora* growths extended from the surface to a depth of 3 metres and then the *Cladophora* gradually decreased at 5 metres. Growths were heaviest on the east side of Kelleys Island around Gull and Kelleys Island shoals. The more turbid waters around the Bass Islands did not permit adequate light penetration for growths in water depths greater than 2 metres. The investigation detected approximately 4 square miles covered with luxurious *Cladophora* growth in the island region above. *Cladophora* nuisance problems have also increased on beaches in Ohio, Pennsylvania and New York in the last several years.

It has been demonstrated that growths are limited in Lake Huron by low phosphorus concentrations (Neil and Owen, 1964). In Lake Erie, where there are local sources of nutrient enrichment and a suitable substrate, lush growths of *Cladophora* occur. Turbidity, which affects light penetration, limits the depth to which *Cladophora* develops. In the eastern basin, production is optimal down to 3 metres but decreases considerably beyond this depth.

Although accurate information on long-term trends in the production of *Cladophora* is not available, indications are that it is becoming more abundant as eutrophication advances. Low water conditions provide a greater area of rock suitable for algal growth. Entensive growths in 1957, 1958, and in the early 1960's were related to reduced water levels. In 1966 and 1967, when water levels were high, decreased production was recorded.

To date, chemical control has not proved itself effective and economical enough for use on a large-scale. It was pointed out in a recent report from the Lake Erie Enforcement Conference Technical Committee that at least 350 square miles of Lake Erie would have to be treated for effective control.

Some degree of success has been achieved by employing mechanical methods to remove shoreline accumulations. Throughout the summer, tractors equipped with rakes and front-end loaders are used at beaches to collect the algae for removal by truck. However, this operation tends to be inefficient and expensive, and cleaning equipment must be employed throughout the summer to cope with repeated accumulations.

Heavy growths of *Cladophora* seriously impair the water for recreational, industrial and municipal usage. Water at the shoreline is in general rich enough to support substantial growths of *Cladophora*, and major areas of growth are determined by depth contour patterns, water turbidity and the presence of suitable substrate. Production seems to be increasing with advancing eutrophication of the lake. More prolific growth is noticeable near local sources of enrichment. Chemical control measures have been tested with little success, and mechanical cleanup measures are inefficient, providing only temporary relief. It is obvious that the best method of controlling the problem lies in the reduction of nutrient input to the lake.

2.4.4 Bottom Fauna

The benthic fauna consists of animals which live on and within the lake bottom sediments. Investigations of the distribution and abundance of benthic organisms yield valuable information about the environment which they inhabit. Characteristics such as the number and distribution of taxa, community balance and total numbers of organisms reflect water quality. A clean-water community has a diversified population which is not dominated by one major group, and a moderate total number of organisms. In comparison, most organically-enriched lake environments support an imbalanced community dominated by very high numbers of tubificid worms. An environment subjected to a toxic pollutant is characterized by an absence of aquatic animals or by very low numbers of a few tolerant organisms. However, natural limitations such as bottom type and water temperature must be taken into account before a valid assessment of water quality can be made on the basis of benthic communities.

Some benthic organisms have been classified, rather non-precisely, as 'pollution-tolerant'. This classification rests on the ability of an organism to withstand periods of deficiency or absence of dissolved oxygen and does not imply that some organisms might prefer a lack of oxygen. Other organisms are often referred to as being 'cosmopolitan' or 'pollution-sensitive', the former referring to organisms inhabiting both polluted and clean-water environments, and the latter referring to organisms that cannot live in polluted water.

To date, the majority of reports published on the bottom fauna of Lake Erie deal only with the western basin. Wright (1955) reported on the organisms found in western Lake Erie during a limnological survey in 1930. Shelford and Boesel (1942) described the benthic communities in the island area of the western basin based on a survey performed in the summer of 1937. Beeton (1965) described the distribution of oligotrophic and eutrophic forms throughout the Great Lakes.

Studies conducted by the U.S. Bureau of Commercial Fisheries between 1929 and 1959 (Beeton, 1961; Wright, 1955) and personnel at the Franz Theodore Stone Institute of Hydrobiology (Britt, 1955a, 1955b) show that significant changes have taken place in populations of bottom-dwelling organisms in western Lake Erie. These workers have shown that pollution-tolerant forms have increased greatly along the west side of the basin and in the island area, particularly sludgeworms, fingernail clams and midge larvae. As an example, in the island area sludgeworms have increased from 10 organisms per square metre in 1929 to 550 organisms per square metre in 1957. During the same period midge larvae increased from 60 to 300 organisms per square metre. The clams showed a threefold increase at two index stations near South Bass Island.

Similar changes were revealed by a comparison of studies undertaken by Wright (1955) in 1930 and Carr and Hiltunen (1965) in 1961. Their reports demonstrate a ninefold increase in the number of sludgeworms, a fourfold increase in the number of midge larvae, and a twofold increase in the number of fingernail clams.

Pollution-sensitive caddisfly larvae (Trichoptera) and burrowing mayfly nymphs (*Hexagenia spp.*) have been drastically reduced in numbers. Beeton (1961) reported that the formerly abundant Trichoptera larvae averaged less than 1/m^2 in 1957. *Hexagenia*, which lives in soft mud and feeds of detritus, was the most common macro-invertebrate in the western basin prior to the early 1950's. Wright (1955) found 285 and 510 nymphs/m^2 in the island area in 1929 and 1930, respectively. He found moderate numbers at each river mouth, and an average of 400/m^2 was obtained for the open-lake. Chandler (1963) summarized studies made between 1942 and 1947 and reported an average of 350 nymphs/m^2 for that period. Wood (1963) found an average of 235/m^2 for 204 samples collected in 1951 and 1952. In June, 1953, Britt (1955a) found approximately 300 nymphs/m^2. After sampling again in September, following a five-day period of thermal stratification and bottom oxygen depletion, Britt found only 44 nymphs/m^2. The succeeding year showed a good recovery, but Beeton in 1959 found only 39/m^2. In June, 1964, United States Public Health Service found only two nymphs in samples from 47 island area sites. A few *Hexagenia* nymphs were found near the Canadian shore at the mouth of the Detroit River in 5 metres of water and near Colchester and Kingsville, Ontario. None were found in the Michigan waters of the basin.

Published quantitative data are not available on the bottom fauna of central and eastern Lake Erie, apart from the recent study of Brinkhurst *et al.* (1968) summarized below. Newspaper articles dating back to 1927 described "immense swarms" of mayflies blown into the city of Cleveland. A decline was first noted in 1949 but they reappeared in 1950 and were reported yearly through 1957. They were not reported after 1958.

This report summarizes more recent findings on the bottom fauna of the western basin, and furnishes background information for future bottom faunal investigations in the central and western basins. A total of 90 stations were sampled throughout the lake by the United States Public Health Service in 1963 and 1964 (Fig. 2.4.6). The Fisheries Research Board cooperated with the Great Lakes Institute of the University of Toronto in analyzing data from 80 stations throughout the lake. The oligochaetes (sludgeworms), midge larvae, and

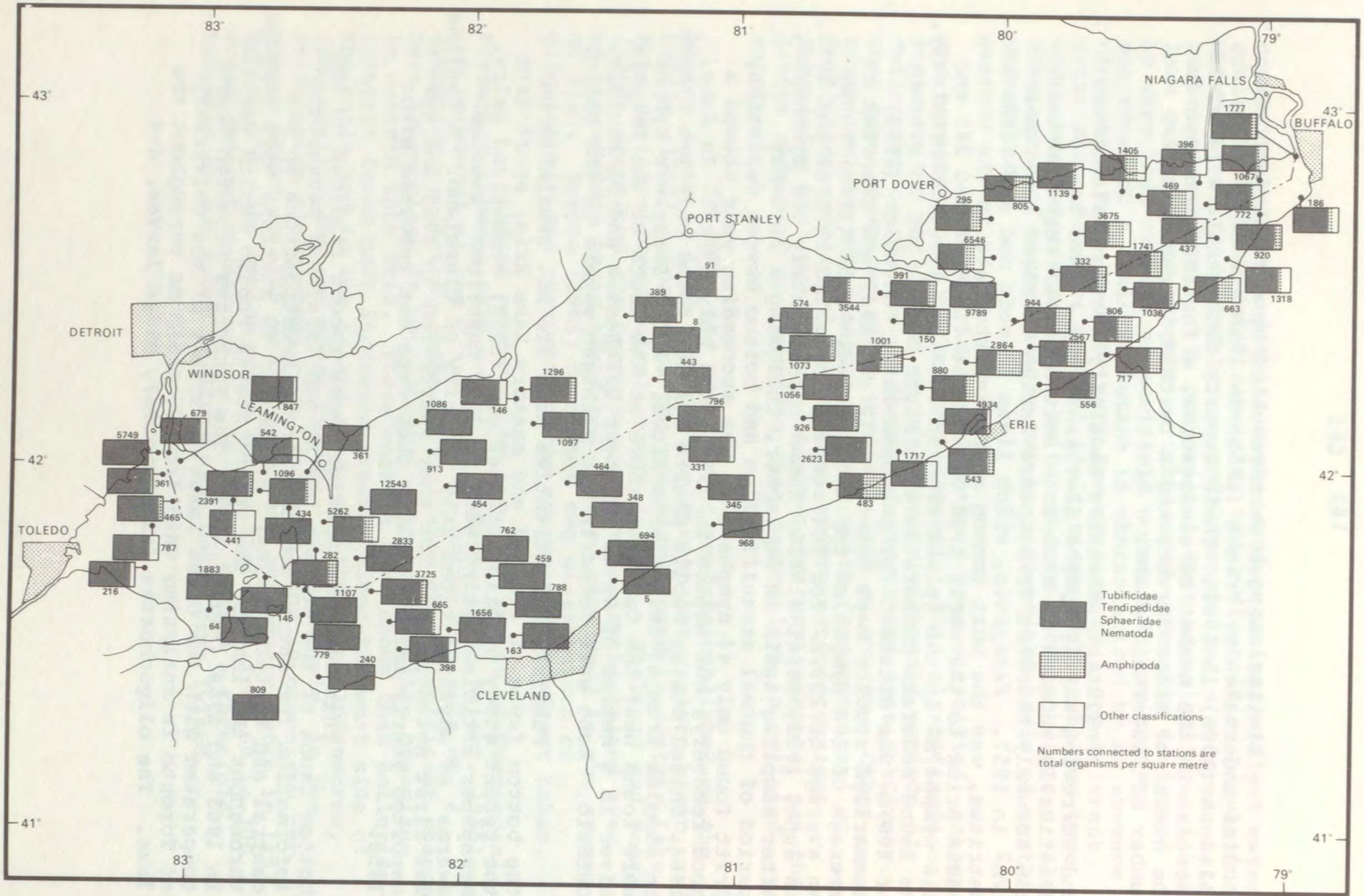


Fig. 2.4.6 Benthic populations in the spring, summer and autumn of 1963 and 1964.

sphaeriid clams (fingernail clams) were studied in detail by Brinkhurst *et al.* (1968). In 1967, OWRC sampled 109 stations in the western basin and nearshore Canadian waters of the central and eastern basins.

Results

One striking feature of the benthos of Lake Erie is the variation in community structure throughout the lake. Each of the three major basins contains a population structure which differs considerably from the other basins.

The United States Public Health Service results of bottom fauna surveys of the offshore waters of Lake Erie are summarized in Fig. 2.4.6 which shows the relative abundance of the pollution-sensitive scud *(Pontoporeia)* to the more tolerant sludgeworms *(Tubificidae)*, bloodworms *(Chironomidae)*, fingernail clams *(Sphaeriidae)*, and nematodes *(Nematoda)*. Fig. 2.4.7 divides the lake into four zones based on benthic populations. It is evident that most of the western and central basins were characterized by a lack of the pollution-sensitive scud and preponderance of pollution-tolerant sludgeworms, bloodworms, fingernail clams, and nematodes. A few areas in the western basin, the eastern part of the central basin, and the eastern basin support a good population of pollution-sensitive scud which are indicative of the more favourable environmental conditions in these areas. The four zones shown in Fig. 2.4.7 are described as follows:

Zone A - Contains only the pollution-tolerant groups: Sludgeworms, fingernail clams, nematodes, and pollution-tolerant species of bloodworms (midges).

Zone B - In addition to groups in Zone A, the following groups of intermediate tolerance were found: aquatic sowbugs, snails, leeches and several additional species of bloodworms.

Zone C - May contain any organisms found in Zones A and B but scuds *(Gammarus fasciatus* and/or *Hyalella azteca)* are always present.

Zone D - May contain any group of organisms listed in Zones A, B, and C but always contains the pollution-sensitive scud *(Pontoporeia affinis)*.

Zones C and D had the greatest variety of bottom-dwelling organisms and were characterized by the presence of scuds at each station. *Gammarus fasciatus* was found regardless

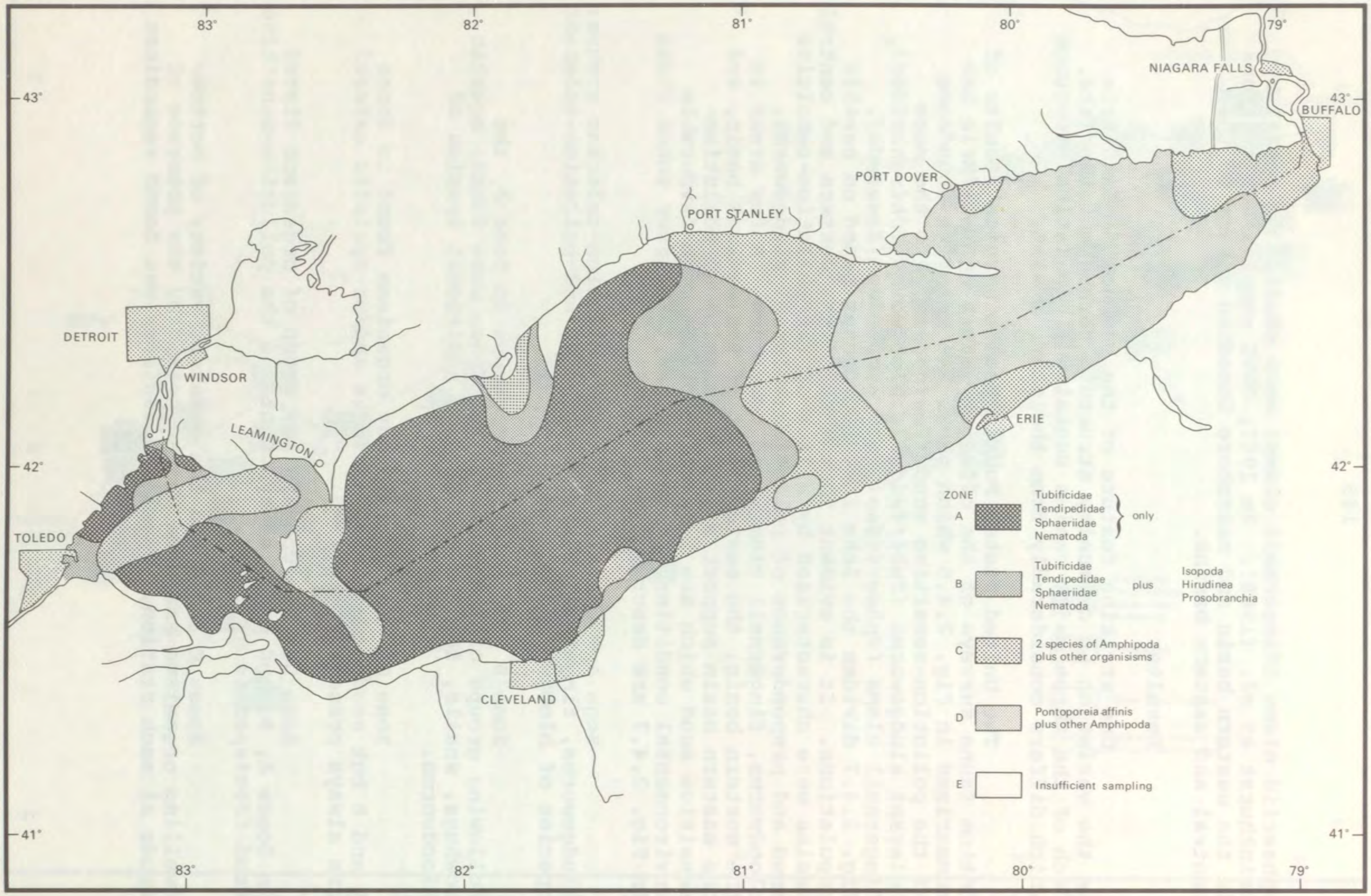


Fig. 2.4.7 Benthic fauna distribution for 1963 and 1964.

of bottom type and *Hyalella azteca* was present at many locations associated with a sand, gravel or rock bottom. *Pontoporeia affinis*, which requires relatively deep and well-oxygenated water, occurred only in Zone D.

Dissolved oxygen data, from studies conducted by the United States Public Health Service, the Bureau of Commercial Fisheries, and the Great Lakes Institute are summarized in Fig. 2.4.8. Zone A coincides approximately with the area in which dissolved oxygen concentrations of less than 2.0 mg/l have been found in the hypolimnion during the summer. Not only were the number of species reduced in the area of low dissolved oxygen, but the total numbers were lower as well (Table 2.4.5). Stations chosen for this comparison were located in areas where a persistent thermocline existed between mid-June and mid-September. Bottom deposits were mostly mud in the low dissolved oxygen area, and mud and sand in adjacent areas.

Low dissolved oxygen not only limits the number of species but limits the population density as well, even though the sediments are high in organic matter.

Zone B of Fig. 2.4.7 is a transition area where the pollution-intolerant scuds, mayflies, unionid clams, and caddisflies were absent. Intermediately tolerant forms such as the aquatic sowbug *(Asellus militaris)*, snails *(Gastropoda)*, and leeches (mostly *Helobdella sp.*) were found. Zone B approximates the area where dissolved oxygen levels were 2.0 to 4.0 mg/l in the hypolimnion during the summer of 1964.

Western Basin

Results of the 1967 OWRC study are illustrated in Fig. 2.4.9, 2.4.10, and 2.4.11. The western basin has been subdivided into five sections (Fig. 2.4.10) according to the similarity of benthic communities and existing physical characteristics.

Stations at the mouths of the Maumee and Raisin Rivers were characterized by extremely low numbers of genera, worm populations greater than 5,000/m^2 (Fig. 2.4.9) and the conspicuous absence of fingernail clams which were otherwise widespread throughout the western basin. Numbers of genera per station at the mouths of both of these rivers never exceeded four (Fig. 2.4.11) and at the station closest to the mouth of the Raisin River, only one genus (a pollution-tolerant tubificid) was found. Off the Raisin River the numbers of genera per station increased and the total numbers of tubificids decreased

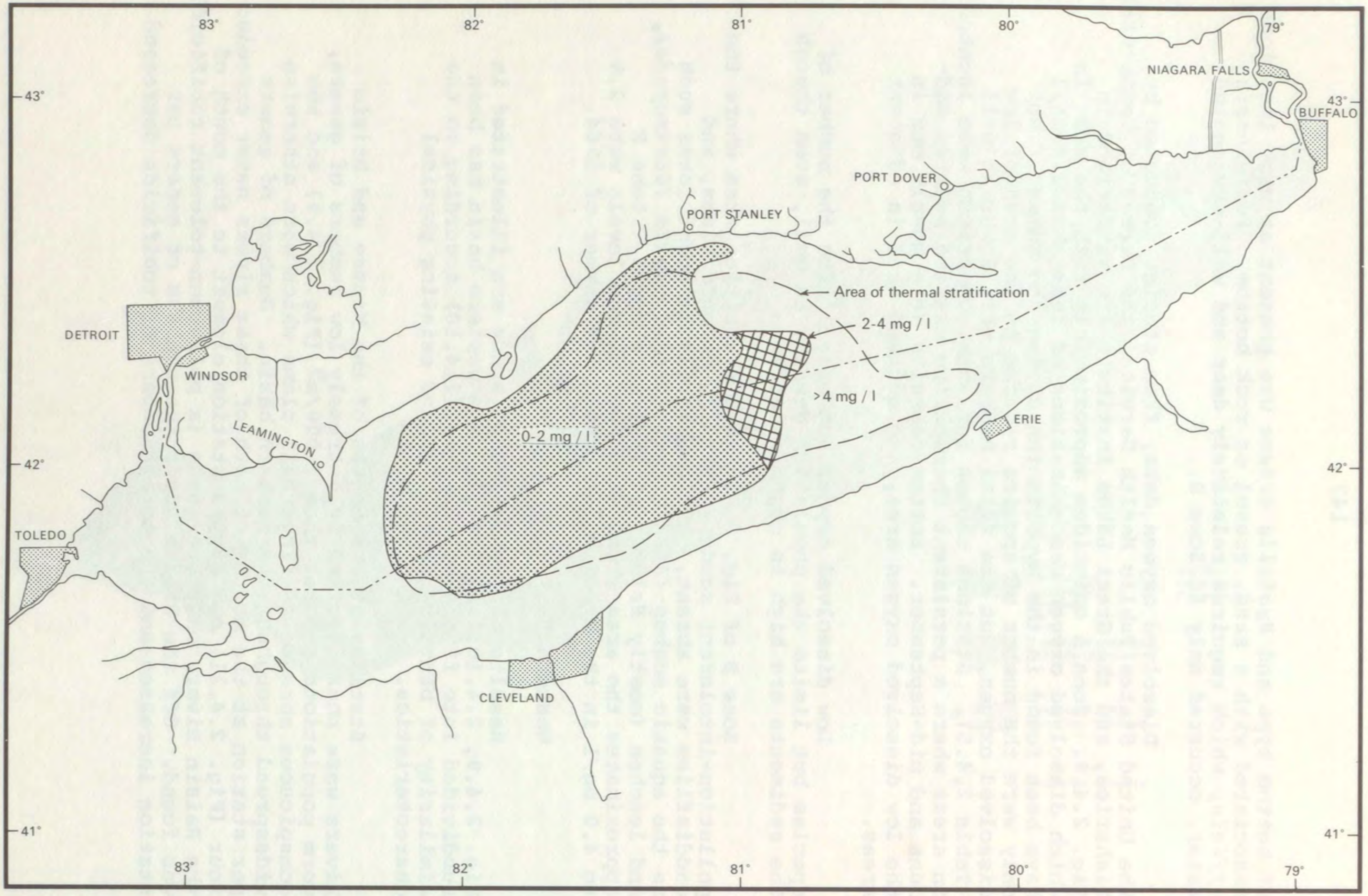


Fig. 2.4.8 Distribution of dissolved oxygen in bottom waters (August, 1964).

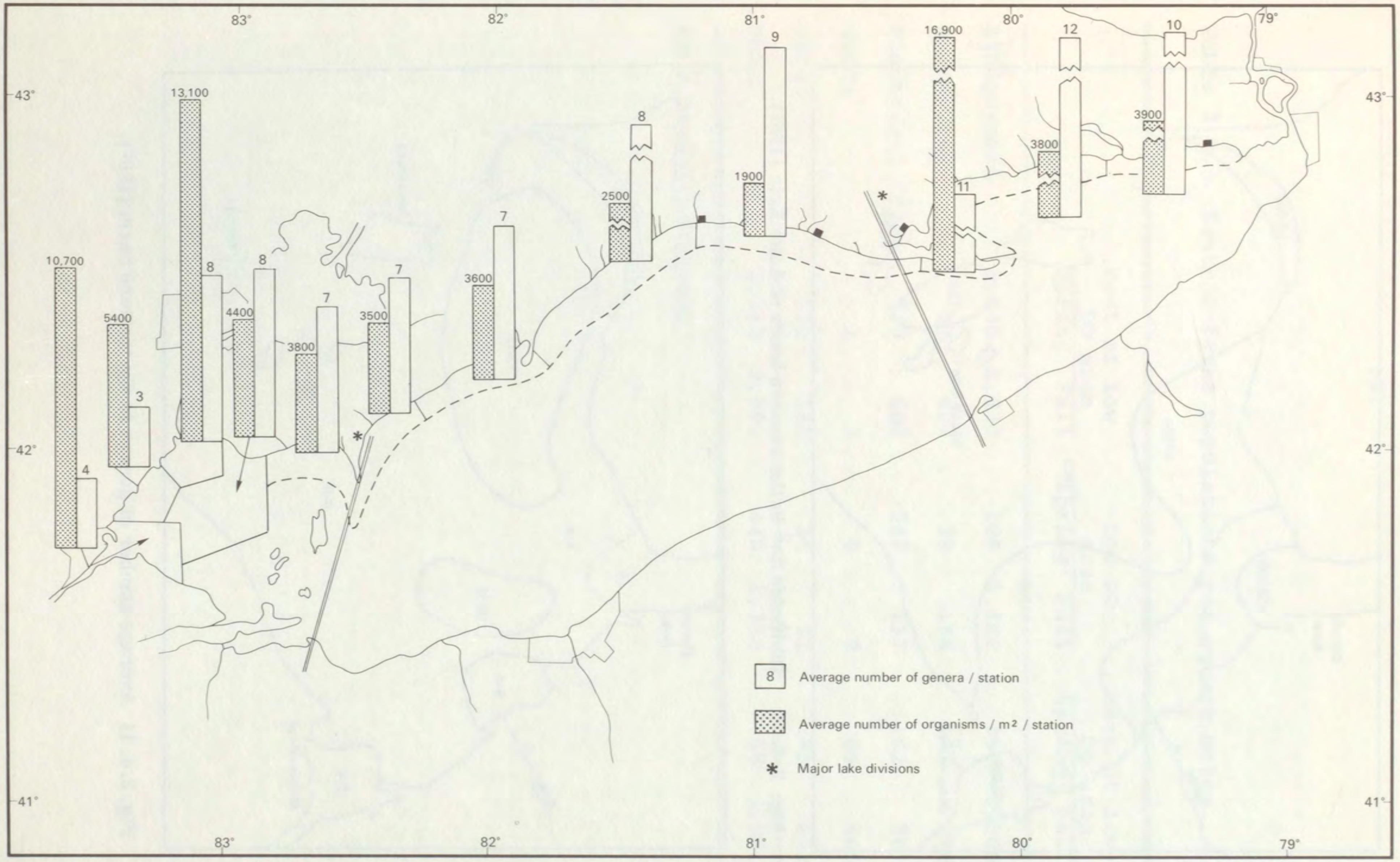


Fig. 2.4.9 Average number of genera and average total number of organisms per station (April to September, 1967).

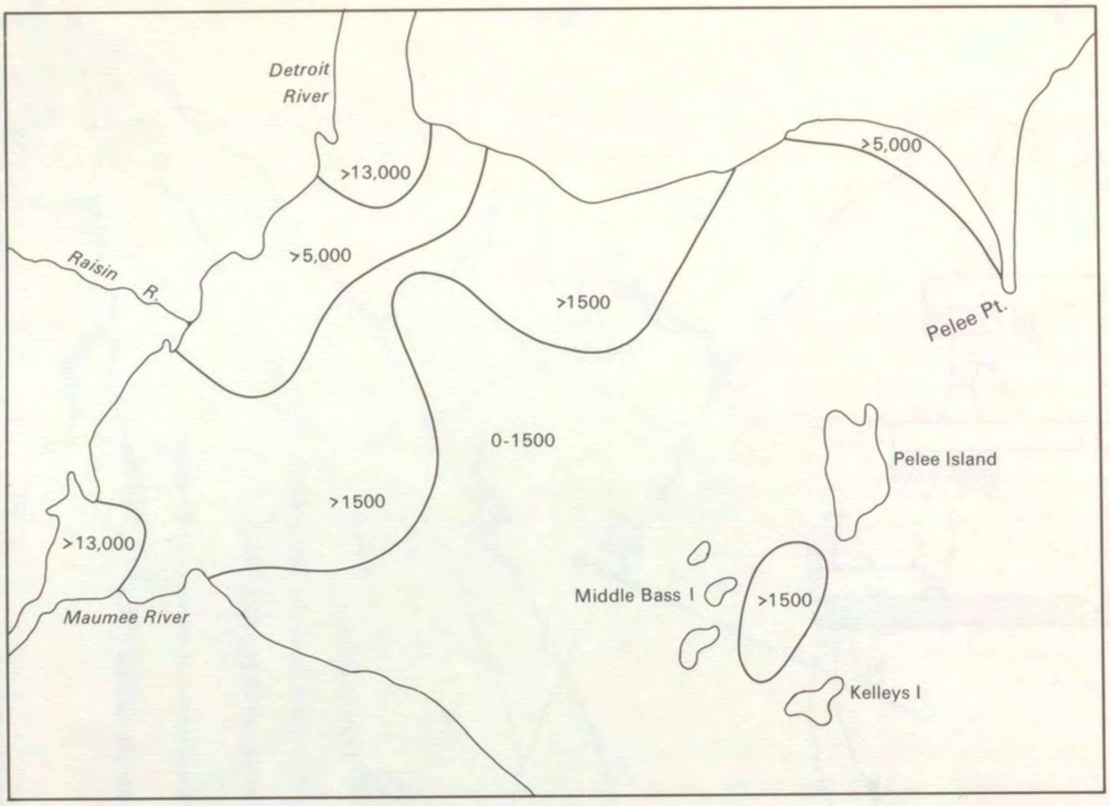


Fig. 2.4.10 Tubificids/m^2 in the western basin of Lake Erie (1967).

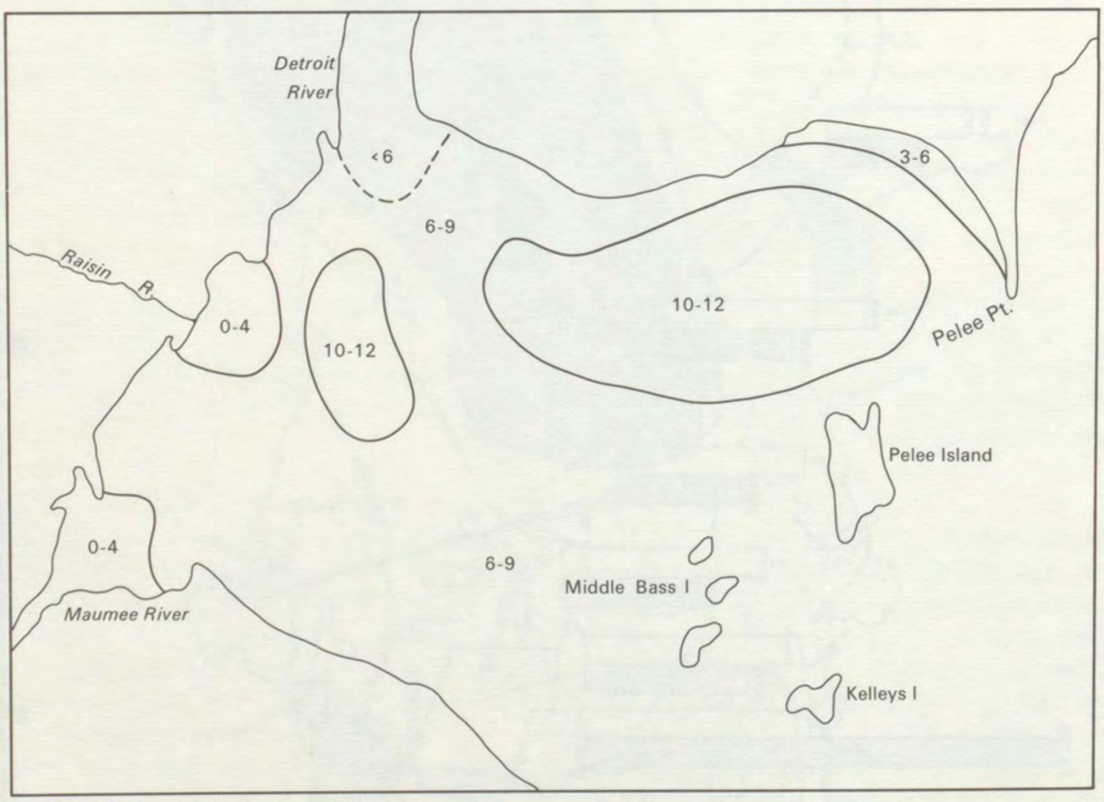


Fig. 2.4.11 Average number of genera in the western basin (1967).

Table 2.4.5 Benthic fauna populations per square metre.

	West of low DO area		Low DO area		East of low DO area	
	Spring	Fall	Spring	Fall	Spring	Fall
Sludgeworms	1,850	1,830	186	1,460	354	2,300
Bloodworms	47	407	39	156	107	278
Fingernail Clams	350	502	187	137	162	307
Scuds	1	7	0	0	69	465
Other	121	145	36	31	73	221
Total	2,369	2,891	448	1,784	765	3,571

DO = Dissolved oxygen

progressively further out in the lake. This fact and the notable absence of fingernail clams indicate the presence of a heavily polluted area at the river mouth. Tubificid populations at two of the Maumee River stations exceeded 10,000/m^2, indicative of excessive organic pollution.

The benthic community at the mouth of the Detroit River was characterized by very high tubificid densities and moderate numbers of genera (Fig. 2.4.10 and 2.4.11). Of the 15 stations in the western basin with populations of tubificids greater than 5,000/m^2, seven fell within the immediate area of influence of this river. Three of the seven stations had numbers greater than 10,000/m^2 including the two closest to the mouth. However, none of the stations yielded less than five genera and the average for stations near the Detroit River mouth was 8 genera per station.

Proceeding south from the Detroit River mouth toward the central portion of the western basin, the numbers of tubificids decreased and the number of genera increased. The zone of heavy organic pollution, as indicated by tubificid populations greater than 5,000/m^2 (Wright, 1955) extended out into the lake about eight miles. Stations following the Michigan shoreline from the Detroit River to the Raisin River supported dense populations of tubificids. The number of genera increased to 12 at a station about 3 1/2 miles off the mouth of the Raisin River. Along the Ontario shoreline recovery commenced after about six miles from the Detroit River mouth. From that point eastward, a wide variety of forms (unionids, snails and a single caddis larva) were found and tubificid counts decreased. These facts indicate that, while the Detroit River has a large impact on the water quality of Lake Erie because of its great flow and total pollutional loading, localized areas of serious degradation also occur at the mouths of the Raisin and Maumee Rivers due to the high concentrations of pollutants.

Another problem area was noted along the western side of Pelee Point, extending into Pigeon Bay near Leamington. Worm counts of greater than 5,000/m^2 and fairly low average numbers of genera per station (Fig. 2.4.10 and 2.4.11) indicated organic pollution in this part of the basin.

It is important to note that Carr and Hiltunen (1965) using bottom fauna parameters, established that water quality in western Lake Erie has been impaired markedly over a 30-year interval. A further decline in water quality has been indicated in the six years following their 1961 study. No *Hexagenia* (mayfly) larvae were recovered in 1967. Two genera of caddisfly larvae were recorded at a total of 13 stations in 1961 while one genus at one station was found in 1967. In 1961, the average number of genera per station ranged from five to seventeen; in 1967, from only one to twelve.

The bottom fauna of this basin reflect the detrimental effects of heavy organic enrichment, siltation and reduced dissolved oxygen tensions. Normal benthic populations have been affected most significantly at the mouths of the Detroit, Raisin and Maumee Rivers and in the area of Leamington in Pigeon Bay.

Central Basin

Benthic communities of the nearshore Canadian waters of the central basin were characterized by a decreasing number of genera and increasing numbers of individuals from east to west (Fig. 2.4.9).

Clean-water forms and a wide variety of organisms were found at stations east of Rondeau. The cold-water amphipod, *Pontoporeia affinis*, occurred only in the most eastern subdivision of the central basin even though sampling depths and bottom types were similar for stations west of Port Stanley where none were found. The low average number of organisms per sample at stations east of Rondeau (2,200/m^2) was likely the result of shifting sands along the exposed shoreline.

Between Rondeau and Point Pelee, the average number of genera per station decreased to 6.9 and the average number of organisms per station increased to 3,550/m^2. Tubificid densities of greater than 5,000/m^2 and an abundance of tolerant midge larvae, *Procladius* and *Chironomus*, occurred at three stations. However, the presence of less tolerant forms and moderate numbers of genera at these three stations dispel suspicions of serious organic pollution in the area.

Worms of the families Lumbriculidae and Naididae were widespread in the central basin, occurring respectively at 45 percent and 15 percent of the stations, the highest percentage occurrence of each in the lake. Most representatives of these families are typical of unimpaired oligotrophic lake environments. Also, certain species of tubificids, *Potamothrix moldaviensis*, which occur under similar conditions, were also recorded most frequently in the central basin occurring at 41 percent of the stations.

Eastern Basin

The nearshore area of the eastern basin was subdivided into three sections (Fig. 2.4.9) according to the similarity of benthic communities and existing physical characteristics.

Conditions in the section which includes the littoral zone of outer Long Point Bay, are governed to some extent by the sheltered location and the morphometry of the area. The highest average number of genera per station occurred in this region. Clean-water mayfly and caddisfly larvae were widespread. Of the 10 stations in the eastern basin where *Pontoporeia affinis* occurred, seven were situated in Long Point Bay. Tubificid densities did not exceed $1,000/m^2$ at these stations. The presence of well-balanced and diversified communities suggested excellent water quality in the littoral zone of this section.

Although communities in the most easterly subdivision of the eastern basin were less diversified, good water quality was indicated. Physical limitations such as the rocky or gravelly nature of the bottom tended to limit the distribution of certain clean-water organisms. Also, the average sampling depth (13 metres) was greater here than in other areas of the eastern basin. The burrowing mayfly, *Hexagenia*, occurred at only one station (sampled in 1966) while caddisfly larvae occurred with about the same frequency as in the Long Point Bay area. Fig. 2.4.9 reveals that a high average number of genera per station was typical for this section even though these physical limitations existed. The average number of organisms per station was similar to the adjacent Long Point Bay section, but was elevated somewhat by high tubificid counts at two stations. The first, just west of Point Abino, had 9,000 $worms/m^2$. Two major groups (worms and midge larvae) made up this community but a good variety within each group (11 genera) was present. Deposition of decaying *Cladophora* and other organic matter was considered to be responsible for the high tubificid count. The other station, one-quarter of a mile out from the mouth of the Grand River supported only four genera in a community composed of 10,900 tubificids and 64 fingernail $clams/m^2$. This imbalance is the result of pollution associated with the river discharge.

The final subdivision of the eastern basin extends along the southern shoreline of Long Point to the boundary separating the eastern and central basins. Sudden changes in depths and bottom types characterize this area, causing marked alterations in the benthos. Four stations were sampled in this subdivision. While an extremely high tubificid density

(43,000/m2) was obtained at one offshore station, probably resulting from heavy deposition of organic material, the remaining three stations were characterized by a diversified fauna.

The eastern basin generally supported well-balanced benthic communities and moderate populations of organisms. Long Point Bay was dominated by clean-water forms. A station at the mouth of the Grand River and a deep station off the lakeward shore of Long Point reflected organic pollution.

In general, there is a gradation in Lake Erie from west to east, ranging from a restricted variety of organisms at the western end, to a diverse fauna in the eastern basin. Several interesting comparisons were made between the macro-invertebrate populations of the western basin and those along the Canadian shoreline of the central and eastern basins.

The average numbers of genera per station varied from 6.4 in the western basin to 7.8 in the central basin and 11.0 in the eastern basin. The numbers of genera per station ranged from 1 to 12 in the western basin, 2 to 12 in the central basin, and 5 to 18 in the eastern basin. Clean-water forms were rarely found in the western basin but were somewhat more common in the central basin and were well represented in the eastern basin. The mayfly genus *Hexagenia* was collected at 24 percent of the stations in the eastern basin in 1967, but was not recovered elsewhere in the study area. Caddisfly larvae occurred at 24 percent of the eastern basin stations, but with the exception of one station in the western basin, were not found at any other location.

Amphipods occurred at 78 percent of the sampling locations in the eastern basin and 35 percent of those in the central basin, but were limited to 14 percent of the stations in the western basin. *Pontoporeia affinis* occurred at 44 percent, 22 percent and none of the stations in the eastern, central and western basins, respectively. Because this species is typical of deep, cold oligotrophic lakes, its distribution in Lake Erie is determined largely by the presence or absence of a hypolimnion.

Conversely, pollution-tolerant invertebrates dominated the western basin. The tubificids, *Limnodrilus hoffmeisteri* and *L. cervix*, attained their highest frequency of occurrence (97.6 percent and 76 percent) at stations in this basin. In the western basin, less tolerant oligochaetes were either not found (*Naididae* and *Lumbriculidae*) or occurred rarely (*Potamothrix moldaviensis* and *Aulodrilus pluriseta*).

Populations of Midge Larvae

The distribution of midge larvae throughout Lake Erie was studied by Hamilton in Brinkhurst *et al.*, 1968. He found that midge populations not unlike the other groups, reflect the change from moderately oligotrophic or mesotrophic conditions at the eastern end of the lake, to eutrophic conditions at the western end. Table 2.4.6 lists the midge larvae collected in each of the three basins. It is interesting to note that only five genera were collected in the western basin, while ten were collected in the central basin, and 14 in the eastern basin. All genera found in the western basin are tolerant of very eutrophic conditions, while those in the eastern basin include several forms indicative of oligotrophic conditions. The midge fauna in the central basin was intermediate.

The two taxa most indicative of the range of conditions occurring in the lake are *Heterotrissocladius cf. subpilosus* and *Chironomus (s.s.)*. *H. cf. subpilosus*, a species common in Lake Ontario and Georgian Bay, was common in the eastern part of Lake Erie, but was not found in the central and western parts of the lake. In contrast, *Chironomus (s.s.)* was more abundant in the western and central basins of Lake Erie than in the eastern basin. In addition the dominant *Chironomus (s.s.)* in the western part of the lake was *C. plumosus* or a closely related species. In the eastern basin *C. cf. anthracinus* and *C. cf attenuatus* were the dominant chironomids, neither indicative of markedly enriched conditions. The findings conform well with Brundin's bottom faunistic lake-type system (Brundin 1956, 1958) as he finds *C. plumosus* to be associated with more eutrophic lakes than *C. anthracinus*.

There is evidence that conditions in the extreme western end of Lake Erie are too severe even for *Chironomus (s.s.)*. Carr and Hiltunen (1965), who sampled this part of the lake in 1961, reported that the only widespread genera were *Procladius*, *Coelotanypus* and *Cryptochironomus*. *Chironomus* was neither widely distributed nor abundant. Sampling by the Great Lakes Institute, University of Toronto, did not extend far into the area sampled by Carr and Hiltunen, but nevertheless *Chironomus (s.s.)* was not as common in the most westerly samples as it was near the eastern part of the central basin. Samples taken nearest the Detroit and Maumee Rivers either contained no *Chironomus (s.s.)* or, when the genus was present, all specimens were badly deformed. Mouth parts exhibited a variety of aberrations, but the most conspicuous feature of these larvae was the exceedingly thick exoskeleton. The maximum thickness of this secreted layer varied in different larvae

Table 2.4.6 Average numbers of Chironomidae collected per hundred dredgings in Lake Erie. Taxa arranged approximately in order of decreasing ability to survive under extreme eutrophic conditions (Brinkhurst *et al.*, 1968).

	Western		Central		Eastern	
	No/100 Samples	%	No/100 Samples	%	No/100 Samples	%
Coelotanypus cf. concinnus	32.6	7.6	1.8	0.5	0.7	0.4
Chironomus (s.s.) spp.	337.2	78.4	249.3	74.4	79.3	38.3
Procladius cf. denticulatus	41.9	9.7	55.1	16.5	75.6	36.5
Cryptochironomus sp.	16.3	3.8	2.7	0.8	14.8	7.1
Microtendipes cf. pedellus	2.3	0.5	9.3	2.8	–	–
Stictochironomus sp.	–	–	4.0	1.2	–	–
Paralauterborniella cf. nigrohalteralis	–	–	0.4	0.1	3.0	1.4
Xenochironomus cf. xenolabis	–	–	–	–	0.7	0.4
Ablabesmyia sp.	–	–	–	–	0.7	0.4
Demicryptochironomus sp.	–	–	–	–	0.7	0.4
Tanytarsus sp.	–	–	9.3	2.8	5.9	2.9
Paracladopelma cf. obscura	–	–	1.3	0.4	1.5	0.7
Micropsectra sp.	–	–	1.8	0.5	1.5	0.7
Monodiamesa cf. bathyphila	–	–	–	–	5.9	2.9
Potthastia cf. longimanus	–	–	–	–	3.7	1.8
Heterotrissocladius cf. subpilosus	–	–	–	–	12.6	6.1
Totals	430.3	100.0	335.0	100.0	206.6	100.0

from 99 to 131 microns (μ). These values are many times higher than normal, and probably are the result of a reaction to an unfavourable environment.

Numerous factors in addition to the trophic condition in a lake can be reflected in the distributional patterns of chironomids. One of the major factors is depth. Many forms are associated with shallow water near the shore and are, in fact, littoral and sublittoral rather than profundal forms. Water temperature is another factor that can be important. *Coelotanypus*, a widespread genus in the southern United States, becomes less common northwards. Lake Erie is close to the northern extent of the known range of this genus, so it is perhaps significant that the larvae appear to be restricted to the western and southern parts of the lake, where the water is usually a few degrees warmer than on the northern shore (Anderson and Rodgers, 1964). In contrast, a number of forms commonly considered as indicative of more oligotrophic conditions are associated with the northern and eastern parts of the lake, where cool temperatures generally prevail. Examples include *Heterotrissocladius cf. subpilosus, Tanytarsus sp., Micropsectra sp., Monodiamesa cf. bathyphila* and *Potthastia cf. longimanus*.

A measure of the trophic condition in Lake Erie, Lake Ontario and Georgian Bay, was calculated as follows (Brinkhurst *et al.*, 1968): The taxa of Chironomidae present were divided into three categories corresponding to their ability to withstand eutrophic conditions. In the majority of cases the placement of particular taxa into the appropriate category posed no serious problem since their environmental requirements are well-documented in the literature. However, in the case of a few of the rarer forms the literature was of little help and hence their rating was primarily a reflection of the types of habitats. The forms in the three categories were assigned index values of 0, 1 and 2 corresponding to their increasing ability to withstand eutrophic conditions (Table 2.4.7). The average index value for all the midge larvae in a particular lake or area was calculated using the following formula to obtain a measure of the trophic condition of the lake. This measurement should not by any means be considered absolute since many factors other than the chironomid fauna can be used to estimate the trophic state of a lake. However, it does provide numerical values as an aid to the comparison of different bodies of water.

Table 2.4.7 Tolerance of profundal Chironomids found in the St. Lawrence Great Lakes to eutrophic conditions (Brinkhurst *et al.*, 1968).

Intolerant (n_0) taxa. index value = 0	Moderately tolerant (n_1) taxa. index value = 1	Tolerant (n_2) taxa. index value = 2
M. cf. bathyphila	*D. cf. vulneratus*	*Chironomus (s.s.)spp.*
P. cf. forcipatus	*P. cf nigro-halteralis*	*Cryptochironomus sp.*
P. cf. longimanus	*Stictochironomus sp.*	*M. cf. pedellus*
H. cf. subpilosus	*Xenochironomus sp.*	*P. cf. denticulatus*
P. cf. obscura	*Ablabesmyia sp.*	*P. cf. bellus*
Tanytarsus sp.	*Thienemannimyia group*	*C. cf. concinnus*
Micropsectra sp.		

$$\text{Trophic condition} = \frac{\Sigma n_1 + 2\ \Sigma n_2}{\Sigma n_0 + \Sigma n_1 + \Sigma n_2}$$

where n_0, n_1 and n_2 refer to the number of intolerant, moderately tolerant and tolerant individuals, respectively.

The calculated values for the areas examined are presented in Table 2.4.8 along with the corresponding catch per hundred dredgings. Theoretical maximum (extreme eutrophy) and minimum (extreme oligotrophy) values are 2.00 and 0, respectively. But in practice it is unlikely that a value of 0 would ever occur because some of the species found in oligotrophic lakes are in fact cosmopolitan species that can live in more eutrophic environments as well. In view of this, the respective values of 2.00 and 0.13 for the western basin of Lake Erie and Georgian Bay represent about as large a difference as one could expect to find, and illustrate how distinct the chironomid faunas and trophic states of these areas are. The "trophic condition" values for Lake Erie become progressively lower toward the eastern end, indicative of the less eutrophic conditions encountered there. The presence of a rather large oligotrophic element in the eastern basin is probably indicative of a more oligotrophic situation than is actually the case. If, as suggested, Lake Erie is undergoing rapid eutrophication then this element may be the remnant of a formerly much more abundant and widespread oligotrophic fauna. Georgian Bay, Lake Ontario and the eastern basin of Lake Erie have many species in common, but as the increasing trophic condition values indicate the oligotrophic elements of their respective faunas become progressively less important in the order given.

Oligochaete Populations

Brinkhurst *et al.* (1968) pointed out that the oligochaetes of Lake Erie are divisible into three associations which occupy zones rougly corresponding to the generally accepted limits of the three lake basins.

The fauna of the basin to the west of the islands was studied in detail by Hiltunen in collaboration with Brinkhurst. They found that oligochaetes were very abundant at the mouths of the Detroit, Raisin and Maumee Rivers, and that the zones have extended since 1930 (Carr and Hiltunen, 1965). *Limnodrilus hoffmeisteri* is the most abundant species of *Limnodrilus (L. claparedeanus, L. cervix,* and *L. maumeensis).* The cosmopolitan *Tubifex tubifex* was only found in one small area at the mouth of the Detroit River. Further out in the western basin other species enter the community, including *Aulodrilus* and *Potamothrix* species, together with *Branchiura sowerbyi* and *Peloscolex ferox* or *P. multisetosus.*

Table 2.4.8 Frequency of Chironomid larvae and calculated trophic condition values for Lake Erie, Lake Ontario and Georgian Bay. Theoretical maximum (extreme eutrophy) and minimum (extreme oligotrophy) values are 2.00 and 0, respectively.

	Chironomids per 100 samples	Calculated trophic condition
Western basin Lake Erie	430.3	2.00
Central basin Lake Erie	335.0	1.91
Eastern basin Lake Erie	206.6	1.67
Lake Ontario	34.6	1.07
Georgian Bay	25.7	0.13

The species found to be most abundant in the central basin was *P. ferox;* a zone of maximum abundance extended diagonally across the basin from northwest to southeast. The possibility that this distribution reflects the path of deposition of organic matter transported into the central basin by the Detroit River cannot be ignored, but the quantitative evidence is weak. *Bothrioneurum vejdovskyanum* was found at eight stations around the western end of the central basin and from a single station in midlake. While *Ilyodrilus templetoni* was scarce, *Potamothrix* was present at nine stations in the central basin and five in the eastern basin. The various *Aulodrilus* species were quite widely distributed, being especially abundant in the shallow parts of the eastern basin. *Psammoryctides curvisetosus* was found only at four stations.

The two species typical of wide reaches of the Great Lakes where there is little evidence of eutrophication (*T. tubifex, S. heringianus*) were found mostly at the eastern end of Lake Erie and in the shallowest parts of the central basin. *Peloscolex freyi* was found only once in the entire series of samples, at a depth of about 15 metres off Erie, Pennsylvania. Hiltunen found *Potamothrix bavaricus* and *Limnodrilus angustipenis* at two stations, the first in the western basin and the second east of Port Dover.

In general, there is a west to east gradation in benthic composition, ranging from those communities indicative of eutrophic conditions in western Lake Erie, to those indicative of moderately oligotrophic or mesotrophic conditions in the eastern basin. This is substantiated not only by general studies on the distribution and numbers of major taxa, but by more detailed evaluations of individual midge and oligochaete populations.

In the western basin, pollution was evident at the mouths of the Detroit, Raisin and Maumee Rivers. As the Detroit River provides 97 percent of the flow into western Lake Erie (Carr and Hiltunen, 1965), the wastes carried to the lake by the river undoubtedly have contributed to the eutrophication of the entire western basin. Comparisons of past and more recent studies indicate that the benthos has changed from a predominance of pollution-sensitive mayfly nymphs, to a predominance of pollution-tolerant sludgeworms and midge larvae.

The benthos of the central basin is characterized by more balanced aquatic communities with the pollution-sensitive *Pontoporeia affinis* in its eastern portion. The presence of water with low concentrations of dissolved oxygen in the deep waters limits the variety and total production of macro-invertebrates there. A study of the nearshore Canadian waters indicated that populations along the western part of the central basin are similar to those in the western basin itself, while populations near Long Point were similar to the "clean-water"type of community found in the eastern basin. Brinkhurst *et al.* (1968) pointed out that while the quantitative evidence is weak, the abundance of *Peloscolex ferox* extending diagonally across the basin from northwest to southeast may reflect the path of organic matter transported into the central basin, which would imply a transboundary movement. It appears that water from the eutrophic western basin is affecting at least the western end of the central basin. Brinkhurst *et al.* (1968) on the basis of midge larvae classify the central basin as eutrophic, whereas in terms of algal abundance it is more mesotrophic in character, at least in offshore waters.

The benthos in the eastern basin is characteristic of a clean-water, moderately oligotrophic environment, perhaps changing to mesotrophy. A particularly wide diversity of organisms exists in Long Point Bay, and the amphipod *Pontoporeia affinis*, plus other pollution-sensitive forms, were found throughout this basin.

2.4.5 Fish Populations

Commercial fish catch statistics and creel census have provided a means by which changes in the magnitude and character of fish stocks can be measured. However, fishing complicates the picture to the extent that interpretation of observed changes is at all times difficult. Pollution effects must be distinguished not only from fishing effects but also from the effects of natural factors in the environment. For these reasons, investigations to date have not yielded much direct evidence casually linking changes in fish populations with changing water quality. However, it is clear that the species remaining are those most associated with a more eutrophic environment and the ones that are declining are those more associated with an oligotrophic environment.

Commercial fish catch statistics gathered by the United States Bureau of Commercial Fisheries have provided a long record of the relative abundance of desirable fish species in Lake Erie (Tables 2.4.9, 2.4.10). In recent years, continuing surveys have been conducted by federal and state agencies on the reproductive phase of the life cycles of fishes and limited predictions of future populations are now possible.

Production statistics indicate that at least six species of fish have declined markedly in the past three decades

Table 2.4.9 Average combined annual United States and Canadian catch for specified periods of major[1] commercial species of Lake Erie (thousands of pounds).

Period	Sturgeon	No. pike	Cisco	Sauger[4]	White-fish	Blue pike[6]	Walleye	Yellow perch	Smelt	Sheeps-head	White bass[4]	Sucker[4]	Channel catfish[6]	Carp	Other[2]	Total production
1879 to 1909[3]	1,052	1,356	25,625	3,700	2,402	10,797[7]	-	2,791	-	1,061	611	1,350	604	2,480	100	53,923
1910 to 1919[3]	77	1,250	27,201	3,656	2,945	9,277	1,756	3,017	-	2,499	383	1,120	1,110	7,544	2,015	63,850
1920 to 1929[3]	39	77	14,126	2,437	1,675	11,292	1,577	5,356	-	2,367	360	1,090	681	3,180	1,476	45,742
1930 to 1934	39	62	764	1,943	2,094	14,623	2,113	12,382	-	2,381	447	1,462	700	2,659	1,594	43,263
1935 to 1939	31	29	1,070	1,414	2,696	18,526	3,515	6,444	-	3,359	655	980	641	2,689	1,964	44,013
1940 to 1944	22	37	283	878	4,058	13,517	3,779	3,869	-	3,624	553	623	948	2,596	1,744	36,716
1945 to 1949	25	21	6,067	567	4,701	12,509	5,807	4,245	-	3,965	701	506	1,093	2,077	2,226	44,510
1950 to 1954	14	12	475	354	2,297	13,535	7,566	6,784	890	3,482	3,485	661	1,589	3,007	973	45,134
1955 to 1959	14	14	128	21	749	10,078	10,267	19,540	4,345	4,020	5,092	413	1,770	4,171	733	61,355
1960 to 1964	4	2	8	1	19	3	1,484	20,219	13,508	5,770	4,111	336	1,484	4,276	792	52,014
Largest catches	5,187	2,973	48,823	6,181	7,098	26,788	15,405	28,954	19,182	6,566	9,024	2,024	2,228	13,419	-	76,313
Year of largest catch	1885	1908	1918	1916	1949	1936	1956	1959	1960	1960	1954	1930	1917	1914	-	1915

[1] Species that have had an annual catch greater than 1 million pounds

[2] Species normally less that 1 million pounds (goldfish, bullheads, burbot)

[3] Average for years or record

[4] U.S. catch only until 1952

[5] Includes bullheads through 1951

[6] Catches of walleye and blue pike combined through 1914

[7] Probably composed of 8 to 9 million pounds of blue pike and the remainder walleye

From "Report on Commercial Fisheries Resources of the Lake Erie basin", U.S. Bureau of Commercial Fisheries, 1966.

Table 2.4.10 U.S. commercial fish catch statistics (annual averages in thousands of pounds).

	Cisco	Sauger	White-fish	Blue pike	Walleye	Yellow perch	Smelt	Sheeps-head	White bass	Sucker	Cat-fish	Carp	Other	U.S. total	Canada total	Total catch
1955	34	15	375	7,648	5,795	2,408	-	1,614	2,931	256	1,947	3,308	465	26,796	30,235	57,031
1956	59	12	445	6,855	6,130	7,054	-	1,924	2,368	269	1,660	3,425	543	30,744	44,682	75,426
1957	23	7	754	3,981	5,035	8,593	2	3,795	1,424	328	1,554	3,768	442	29,706	37,105	66,811
1958	14	2	177	576	3,961	7,061	1	2,816	942	244	1,472	4,880	429	22,575	30,751	53,326
1959	16	1	46	32	1,168	9,348	15	4,608	818	249	1,429	4,015	238	21,983	31,597	53,580
1960	12	2	15	7	1,171	6,390	28	5,098	1,739	250	1,619	4,572	315	21,218	29,219	50,437
1961	6	-	6	2	805	3,694	16	5,764	2,192	330	1,626	4,698	424	19,563	35,698	55,261
1962	5	-	3	1	433	7,548	74	3,524	1,390	261	1,127	4,764	530	19,660	44,464	64,124
1963	1	-	6	-	800	5,822	306	4,126	1,153	224	1,090	3,338	372	17,238	34,233	51,471
1964	-	-	2.8	-	564	1,519	446	4,549	1,535	239	1,163	2,909	400	13,327	25,381	38,708
1965	1	-	6	-	438	3,157	3	4,086	1,110	1	990	3,191	542	13,525	35,096	48,621
1966	-	-	3	-	354	4,063	9	2,156	1,222	187	743	3,702	259	12,698	41,426	54,124
1967	-	-	3	-	511	3,365	3	2,559	1,099	177	655	3,042	201	11,615	37,770	49,385
1968	-	-	2	-	544	3,734	1	3,145	728	141	769	2,683	203	11,950	39,416	51,366

(Table 2.4.10). The sturgeon almost disappeared from catch statistics at about the turn of the century. The cisco, once the dominant species of the commercial catch, experienced a sudden decline in 1926, showed a slight recovery and declined to insignificance in 1957. Whitefish declined drastically in the commercial catch in 1955. The walleye began a drastic decline in 1957 and is still in great distress. The blue pike, which formerly contributed several million pounds per year to the commerical catch became virtually extinct in 1958. Suckers have shown a continuous decline, although to a lesser degree (Table 2.4.9). Yellow perch is the only plentiful fish remaining of the former many prized varieties. The smelt is now commercially exploitable and it, along with yellow perch, is sustaining the fishing industry in Lake Erie.

The capability of Lake Erie to support fish, considered as a total population of all species, has apparently been maintained and may be increasing. This means that the habitat is changing in favour of such fish as carp, alewife, shad, sheepshead, etc. These are generally considered as indicators of general water quality degradation.

Adult and near-adult fish kills in Lake Erie have occurred on various occasions for many years. These kills are not associated with the decline of desirable species. Species susceptible to kills have commonly been perch, white bass, alewife, smelt, gizzard shad, and carp. Kills are more common in the months of June and August. Occasionally, a local kill may result from the discard of fish by commercial fishermen. It does not appear that fish kills have had a measurable effect on the viability of any species in Lake Erie.

While intensive fishing is recognized as contributing to the reduction in desirable fishes (Regier *et al.*, 1968), fishing is by no means the only factor. Failure to reproduce has also been cited by Beeton (1965) in the decline of the commercially desirable species. Certainly this is the case for the blue pike which has failed to spawn successfully since 1953. It may also be said that low levels of recruitment have prevented any appreciable recovery of the other diminished species with the exception, perhaps, of the walleye.

Regier *et al.* (1969), after reviewing the literature and consulting biologists and fishermen connected with the Lake Erie fishery, expressed the belief "that some of the runs (walleye) were destroyed by pollution, and that some of the remaining spawning runs still in use have been impaired by pollution". In support of this view, these authors refer to changes in the boundaries between various types of deposits, rock and mud, to organic deposits on deep reefs that were previously clean, and to increasing algal growth on certain other spawning grounds. Blue pike and sauger which are closely related to the walleye might be similarly affected, and this could likewise be the case with lake herring and whitefish since they also spawn over rocky and gravelly shoals. The spawning requirements of other dominant species such as perch, alewives and white bass are less narrow. This may account, in part, for their numbers being sustained.

It can be inferred from published data on limnological changes in Lake Erie that some deep parts of the lake no longer form a suitable habitat for fish life on a continuing basis. Some of the oxygen levels encountered would, in fact, be lethal over long periods if not evaded by fish. The declines in whitefish and lake herring are likely associated, to a degree, with low oxygen tensions in portions of the hypolimnion. There is reason to believe that the blue pike, which prefers cool water, also has been affected in that regard.

The lack of oxygen at the bottom interferes with the normal habit of percids (perch), centrarchids (bass), ictalurids (catfish), catastomids (suckers) and some cyprinids (minnows) forcing them to vacate areas which in other respects are suitable.

It is presumed that the striking reduction in mayfly larvae in the western basin of Lake Erie resulted from the low oxygen content of the bottom waters (Britt, 1955b). Whether fish distribution or numbers have also been seriously affected is not known.

As a result of the decrease in blue pike and walleye, both terminal predators, forage species such as perch, alewives and smelt have substantially increased in numbers and now form a major part of the fish biomass. To the extent that pollution has affected predator numbers, pollution can be held responsible for this imbalance.

In summary it is probable that pollution and eutrophication have acted to limit reproduction by altering and reducing spawning areas and otherwise restricting the habitat of various fishes, particularly the cold water varieties. These changes are at least partly responsible for declines in some valuable commercial species including the whitefish, lake herring, blue pike, sauger and walleye. The production of certain fish food organisms, notably mayflies and their larvae, has been reduced. To the extent that pollution has affected blue pike and walleye, it has also upset the balance of predator and prey species. This has resulted in excessive dominance by yellow perch, smelt and alewives in the ecosystem.

2.5 BACTERIOLOGY

2.5.1 Bacteriological Parameters

Coliforms

The group of bacteria most indicative of pollution encountered in the bacteriological analysis of water is the coliform group. This group of organisms includes three important biotypes; *Enterobacter* and *Citrobacter* which are usually found on plants and grains, in the soil and to a small extent in human and animal feces; and *Escherichia*, which originates in the intestinal tract of man and animals. Although the coliform group is not normally regarded as pathogenic, the presence of members of this group in water serves as an indication of the potential presence of the scarcer, and much more difficult to isolate, pathogenic enteric organisms, such as those causing typhoid fever, dysentry and cholera. Standards for water quality are based to a large extent on coliform numbers.

It is generally agreed that waters with coliform counts above 20,000/100 ml are unacceptable for drinking water supplies even with conventional treatment. However, waters with counts of 5,000/100 ml or less are acceptable for drinking water supplies with conventional treatment. Waters with counts of 1,000/100 ml or less are acceptable for bathing (McKee and Wolfe, 1963).

Two procedures are commonly used to determine the density of coliforms in water. The oldest and probably the most widely practiced technique for enumerating coliforms is the most probable number (MPN) test. This statistically-oriented technique is based on the ability of coliform organisms to grow in lactose broth with the production of acid and gas within 48 hours at 35°C. A newer and more practical technique, especially for field and shipboard studies, is the membrane filtration (MF) technique. This procedure is based on the filtration of an aliquot of water through a membrane filter with subsequent incubation of the filter on a media soaked pad at 35°C for 24 hours. Coliform colonies are counted and calculated in terms of coliforms per 100 millilitres (ml) of water sample. Data obtained by either technique, (MF) or (MPN), are equally valid even though they are not completely compatible in biotype selection. The work load and lack of space on board the survey vessels used in recent studies led to the adoption of the membrane filtration technique for the estimation of coliform densities.

Fecal Coliforms

Many bacteriologists have suggested that the incidence of *E. coli* Type I in water is a more accurate indication of fecal contamination than the more inclusive "coliform group". These suggestions are based on the fact that *E. coli* Type I is the predominant coliform organism found in the feces of warm-blooded animals. However, there is little justification for applying the "non-fecal" label to the other coliform biotypes, as they are all usually found in small numbers in the feces of most animals and man.

Fecal Streptococci

Sewage contains fecal streptococci in appreciable numbers but not generally exceeding about one-tenth the number of *E. coli*. Therefore, fecal streptococci are used as an indication of pollution on the same grounds as *Escherichia coli*, namely that they are present in feces and sewage and are found in known polluted waters; are not found in pure waters, virgin soil and sites out of contact with human and animal life; and they do not usually multiply outside the animal body. The test for fecal streptococci is of greatest value when coliform organisms are present in the absence of *E. coli* strains, and there is some doubt as to the fecal origin of the bacterial contamination.

Standard Plate Count

The standard plate count test is a means of measuring the number of viable bacteria which are able to grow and multiply in a specific culture media at a specified temperature.

The 20°C standard plate count provides information on the amount of decomposing organic matter available in the water for bacterial nutrition. The majority of colonies that develop at 20°C are non-pathogenic to humans, however, they do provide an indication of the amount of extraneous organic matter available for bacterial nutrition that has gained access to the water from various sources. Generally, the greater the amount of organic matter present, the more likely is the water to be contaminated with potentially pathogenic organisms.

The 35°C standard plate count is a more important index of pollution. The majority of organisms which develop at this temperature are chiefly of soil, sewage or intestinal origin. Thus, the greater the 35°C count the more likely it is that pathogenic organisms will be found.

It has generally been found that in pure water about 10 times as many organisms develop at 20°C than at 35°C; in polluted water this ratio is less, and in chlorinated waters the 20°C and 35°C counts may be almost equal.

Coliform Classification

Pure culture studies enable the bacteriologist to relate coliform biotype incidence to the possible nature and source of bacteriological pollution. Coliform colonies selected for pure culture study are identified by use of biochemical tests and in some instances by means of serological techniques.

2.5.2 <u>Distribution</u>

Lake Erie

The United States Public Health Service conducted a bacteriological investigation of Lake Erie and its drainage basin in the spring, summer and fall of 1963 and 1964. NHW conducted water quality studies of Lake Erie in 1966 and 1967 (Dutka *et al.*, 1967 and Menon *et al.*, 1967). The data obtained from these studies are very similar; however, several areas observed in 1963 to 1964 recorded higher bacterial densities than those observed in 1966 to 1967. Greater statistical significance can be attached to the data obtained from the 1966 to 1967 study due to the more intensive nature of this study.

The highest bacterial counts for the majority of the parameters studied were observed in the western basin during the 1966 to 1967 study. The majority of the offshore sampling stations had median coliform membrane filter densities of 5 or less coliforms per 100 ml, and 1 or less fecal coliforms and fecal streptococci per 100 ml of water sample (Fig. 2.5.1). The western basin also had the highest median 35°C and 20°C standard plate counts with densities of 180 and 280 colonies per ml, respectively (Dutka *et al.*, 1967 and Menon *et al.*, 1967).

Samples collected immediately outside of the Toledo Harbour in the Maumee River recorded some of the highest counts obtained from Lake Erie during the 1967 study (Menon *et al.*, 1967). Data collected from the western basin in 1963 to 1964 indicate that there was a consistent and significant increase in bacterial densities at all depths at the inflow areas of major tributaries (Federal Water Pollution Control Administration, 1968). It is also evident from these data and data collected by the International Joint Commission Field

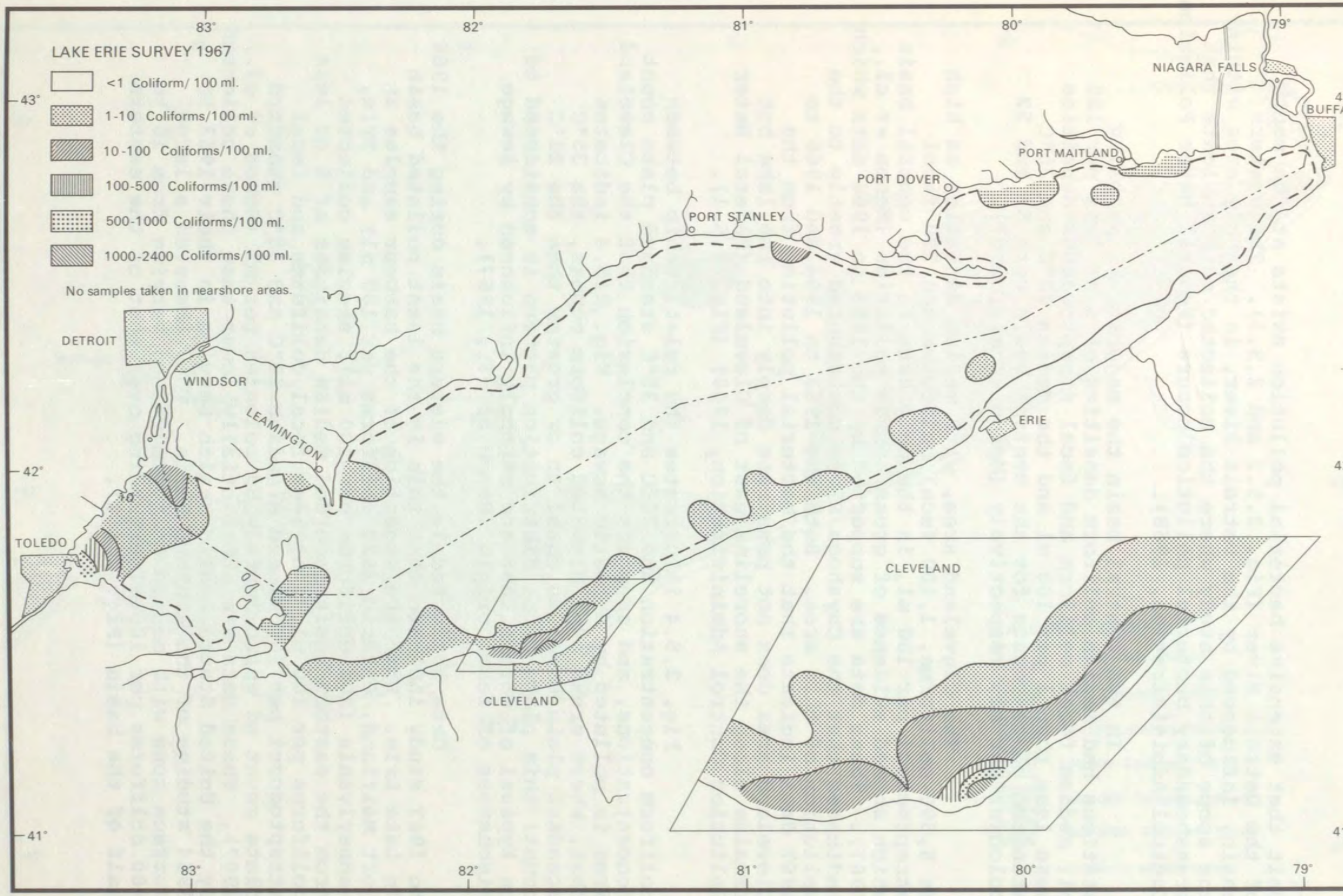


Fig. 2. 5. 1 Summary of coliform MF data for all depths, 1967.

Unit that extensive bacterial pollution exists at the mouth of the Detroit River (Fig. 2.5.2 and 2.5.3). The western basin, influenced by the Detroit River, is the only area within the scope of this study where the collected data indicate that transboundary bacterial pollution occurs (Federal Water Pollution Control Administration, 1968).

In the central basin the majority of sampling stations had median coliform densities of 5 or less per 100 ml; median fecal coliform and fecal streptococcus densities were less than 1 per 100 ml and the median 20°C and 35°C standard plate counts for the central basin were 82 and 52 colonies per ml, respectively (Menon *et al.*, 1967).

The Cleveland area, with median densities as high as 6,500 coliforms, 1,100 fecal coliforms and 330 fecal streptococci per 100 ml, is the only area in the central basin which showed evidence of gross sewage pollution (Menon *et al.*, 1967). These data are supported by the 1963 to 1964 data which indicated that the Cuyahoga River contributed greatly to the pollution of this area. Both the 1963 to 1964 and 1966 to 1967 data indicate that the bacterial pollution from the Cleveland area does not penetrate deeply into the lake but remains along the shoreline east of Cleveland (Federal Water Pollution Control Administration, 1968) (Fig. 2.5.1).

Fig. 2.5.4 illustrates the relationship between coliform concentration and 20°C and 35°C standard plate count concentrations, and supports the conclusion that the Cleveland area is polluted by domestic sewage. Fig. 2.5.4 indicates that, where areas have elevated coliform counts, the 35°C standard plate count is equal to or greater than the 20°C count; this plate count distribution pattern is considered to be typical of waters that are strongly influenced by sewage discharges of fecal origin (Menon *et al.*, 1967).

Data collected in the eastern basin during the 1966 to 1967 study indicate that this is the least polluted basin in Lake Erie. With the exception of the harbour samples at Port Maitland, Ontario (650 coliforms per 100 ml) and Erie, Pennsylvania (300 coliforms per 100 ml), samples collected from the eastern basin recorded median densities of 5 or less coliforms per 100 ml, 1 or less fecal coliforms and fecal streptococci per 100 ml and a median 20°C and 35°C standard plate count of approximately 50 colonies per ml (Menon *et al.*, 1967). These data are substantially lower than those collected by the United States Public Health Service in their 1963 to 1964 studies of the eastern basin. They observed a large surface zone with median coliform values varying from 10 to 100 coliforms per 100 ml extending over most of the eastern half of the basin (Fig. 2.5.2).

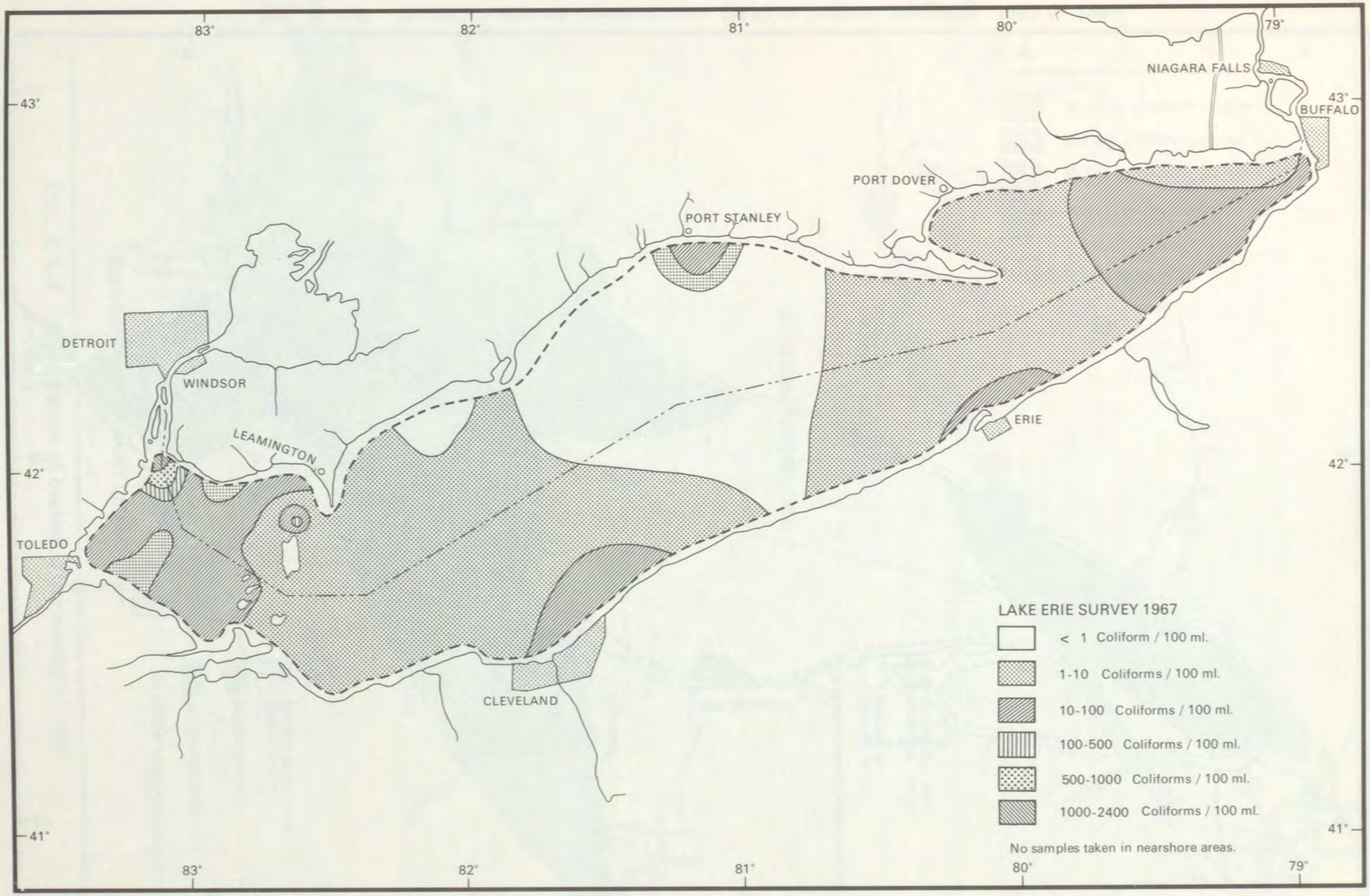


Fig. 2.5.2 Median coliform concentration (MF) in surface samples, 1963 to 1964.

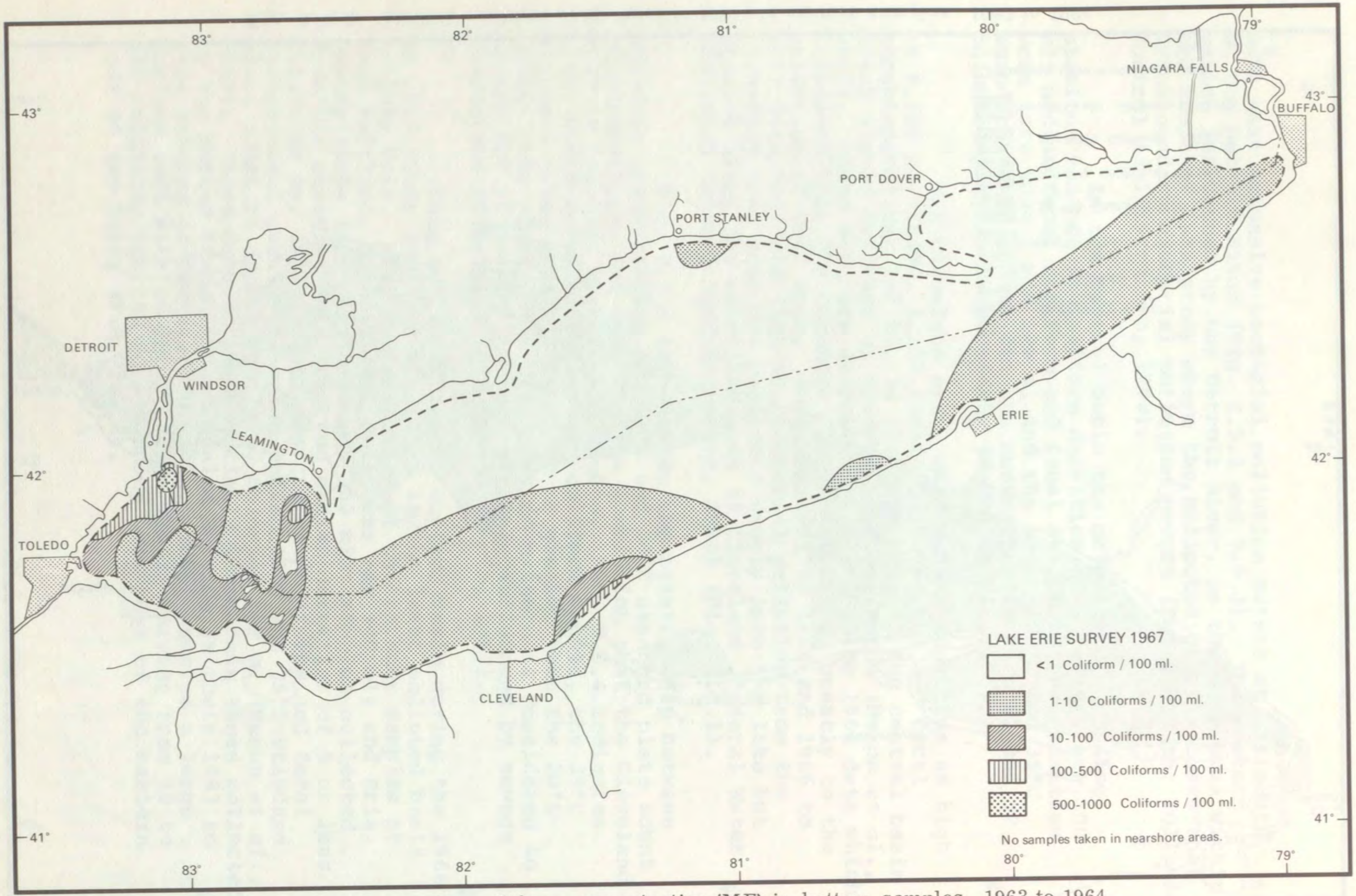


Fig. 2.5.3 Median coliform concentration (MF) in bottom samples, 1963 to 1964.

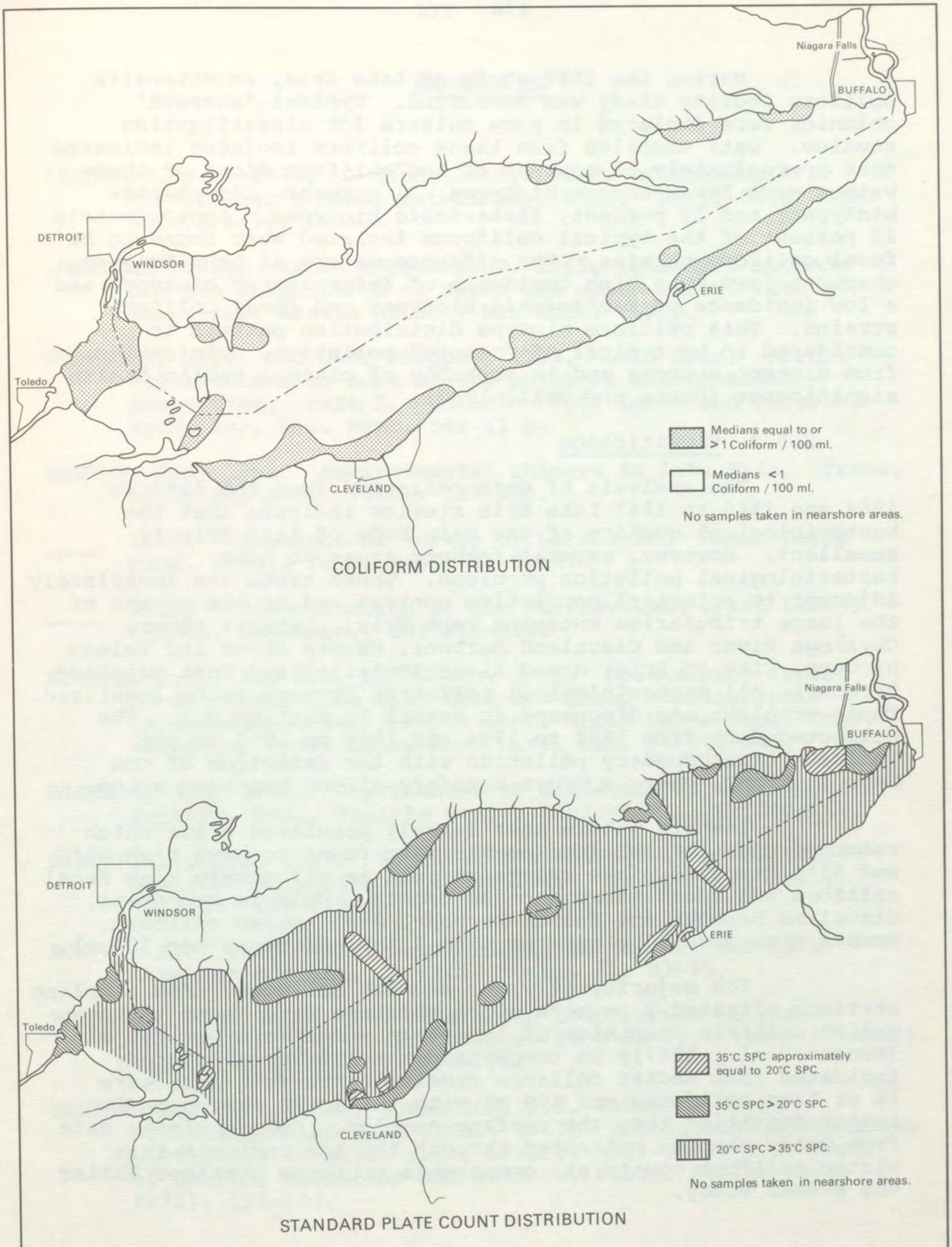


Fig. 2.5.4 Distribution of bacterial parameters, 1967.

During the 1967 study of Lake Erie, an extensive coliform isolate study was conducted. Typical "sheened" colonies were isolated in pure culture for classification studies. Data compiled from these coliform isolates indicated that approximately 50 percent of the coliform flora of these waters were *Enterobacter* biotypes; 21 percent, *Citrobacter* biotypes; and 17 percent, *Escherichia* biotypes. Approximately 25 percent of the typical coliforms isolated were found to be fecal coliform strains. The offshore waters of Lake Erie are characterized by a high incidence of *Enterobacter* biotypes and a low incidence of *Escherichia* biotypes and fecal coliform strains. This coliform biotype distribution pattern is considered to be typical of "remote" pollution, originating from distant sources and is probably of minimal public health significance (Dutka and Bell, 1967).

2.5.3 Significance

The analysis of data collected from the 1963 to 1964 and 1966 to 1967 Lake Erie studies indicate that the bacteriological quality of the main body of Lake Erie is excellent. However, several inshore areas do have bacteriological pollution problems. These areas are immediately adjacent to principal population centres and at the mouths of the large tributaries entering Lake Erie: Detroit River, Cuyahoga River and Cleveland Harbour, Maumee River and Toledo Harbour, City of Erie, Grand River (Ontario) and Port Maitland Harbour. All bacteriological pollution appears to be localized. These problems are discussed in detail in Section 3.2. The collected data from 1963 to 1964 and 1966 to 1967 do not indicate transboundary pollution with the exception of the Detroit River, where a cross-boundary effect has been noted.

Inshore waters near densely populated areas which recorded elevated coliform counts were found to have high 20°C and 35°C standard plate counts as well as relatively high fecal coliform and fecal streptococcus counts. Only in two areas, Cleveland Harbour and Toledo Harbour, were median coliform counts observed to be greater than 2,400 coliforms per 100 ml.

The majority of water samples collected from sampling stations situated 2 or more miles offshore were found to have median coliform densities of less than 1 coliform per 100 ml (Menon *et al.*, 1967); in comparison the 1963 to 1964 study indicated that median coliform densities for this area were 10 or less coliforms per 100 ml with the lower depths having lesser densities than the surface samples. Sparse winter data from water samples collected through the ice indicate that winter coliform counts are comparable to those obtained during the summer study.

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3. SOURCES, CHARACTERISTICS AND EFFECTS OF MATERIAL INPUTS

3.1 SOURCES AND CHARACTERISTICS

Wastes and other materials entering Lake Erie include those discharged at the lake shore by municipal sewerage systems, industries and tributaries. While the tributaries contain a mixture of municipal, industrial, agricultural wastes and land drainage, other sources include vessel wastes, dredging spoils, oil and gas drilling wastes, sediments and natural inputs.

The following discussion describes in some detail the direct municipal and industrial waste inputs. Tributary discharges are described in terms of total loads of various constituents with a further breakdown as to the origin of the nutrients, phosphorus and nitrogen. The locations of direct-lake discharges of municipalities, industries and tributaries are shown in Fig. 3.1.1.

The influence of wastes from shipping, spoils from dredging, sediment accumulations and the nutrient supply from the atmosphere are also discussed. The waste inputs are related to their effects on water quality and water use.

3.1.1 Municipalities

Municipal wastes may seriously degrade water quality in the vicinity of an effluent discharge. The wastes can contribute to sludge deposits, depleted oxygen concentrations, and elevated bacterial levels, dependent upon the type and magnitude of the waste discharge and the rate of mixing and diffusion in the lake. Municipal effluents contain large amounts of the nutrients, nitrogen and phosphorus.

Some large metropolitan areas such as Windsor, Detroit, Toledo, and part of Cleveland discharge wastes to tributaries near their mouths. They are excluded from Table 3.1.1, since wastes are included with tributary discharges. The Buffalo sewage treatment plant is included in the Lake Ontario Volume of this report since its discharge is to the Niagara River.

The Cleveland Easterly and Westerly sewage treatment plants and the plants serving Erie, Pennsylvania, are the three largest individual sources of municipal waste inputs discharging directly to the lake. These three plants contribute 73 percent (2,000 short tons/year) of the phosphorus load and 66 percent

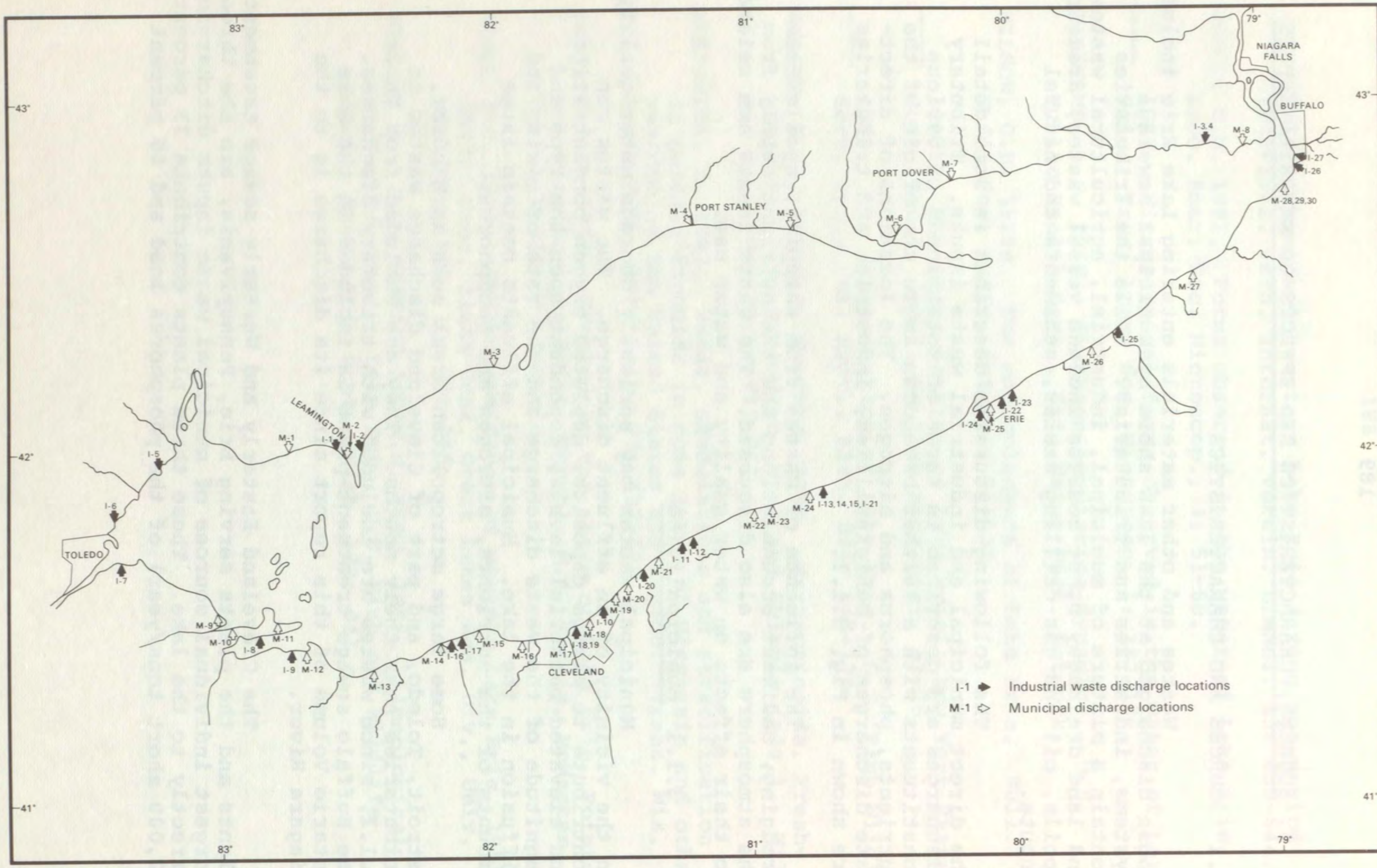

Fig. 3.1.1 Sources and locations of industrial and municipal wastes - Lake Erie.

(6,250 short tons/year) of the nitrogen load of the municipalities listed in Table 3.1.1. No large population centres exist along the Canadian shore of Lake Erie and as a consequence Canadian inputs are relatively small compared with the United States inputs. Other important sources of wastes discharging directly to the lake originate in Euclid, Rocky River, Lorain and Sandusky, Ohio.

Direct municipal lake sources account for about 10 percent of the total phosphorus load to Lake Erie, about 5 percent of the total nitrogen load, and about 10 percent of the biochemical oxygen demand.

Table 3.1.1 does not include data on overflows from combined sanitary and storm sewer systems. Combined sewer systems are usually designed to carry storm flows of about two to two and one-half times dry weather flows with diversion of excess to natural drainage channels. The diverted flow consists of a mixture of untreated sanitary sewage and storm runoff and usually contains high concentrations of BOD_5, suspended solids, and bacteria.

3.1.2 Industries

Information is not complete on these inputs, but Tables 3.1.2 and 3.1.3 indicate that industries contribute large quantities of oxygen-consuming wastes, oil, and suspended and dissolved solids. Eleven power generating plants contribute heat and suspended solids in gross quantities. While not a direct source of oxygen demand, waste heat lowers the level of oxygen saturation of water, affecting the adjacent shore waters of the lake.

Most of the major industrial waste producers are located in or near the large municipalities, and augment the waste load in these areas. All but four industries discharging directly to Lake Erie are on the United States side.

3.1.3 Major Tributaries

Most major tributaries carry significant waste loads and convey materials from upstream municipalities, industries, agricultural sources, and land runoff. The municipal and industrial sources contribute effluent discharges from organized waste collection and treatment systems. Drainage from agricultural lands may contain sediments, pesticide residues, dissolved solids including nutrients, and oxygen-consuming substances. Where these tributaries enter the lake near large direct sources of municipal and industrial waste inputs, the

Table 3.1.1 (cont'd)

Municipalities	Map index[1]	Existing treatment	Sewage flow (mgd)	Population served with sewers (thousands)	BOD_5	Total solids	Total[2] nitrogen (N)	Total[2] phosphorus (P)	Chlorides[2]
CENTRAL BASIN (cont'd)									
Rocky River SD 6	M-16	Intermediate S	4.8	56.0	740	480	390	90	860
Cleveland Westerly	M-17	Primary S-C	34.1	300.0	7,000	6,300	2,100	410	4,600
Cleveland Easterly	M-18	Secondary S-C	122.0	630.0	4,300	3,900	3,400	1,300	9,600
Euclid	M-19	Intermediate S	14.6	123.4	1,800	1,800	860	140	1,900
Willoughby-Eastlake	M-20	Intermediate S	2.9	37.3	280	330	260	50	570
Lake County SD Willoughby-Mentor	M-21	Intermediate S	1.82	32.5	150	170	220	40	500
Lake County SD 1	M-22	Primary S	1.14	7.5	100	50	50	7	110
Geneva-on-the lake	M-23	Primary S	-	.7	70	50	5	9	10
Ashtabula	M-24	Intermediate S	5.0	25.1	730	20	170	50	380
TOTAL					19,301	15,503	8,334	2,326	20,478

Table 3.1.1 Municipal waste discharges direct to Lake Erie 1966-67 (short tons/year).

Municipalities	Map index[1]	Existing treatment	Sewage flow (mgd)	Population served with sewers (thousands)	BOD_5	Total solids	Total[2] nitrogen (N)	Total[2] phosphorus (P)	Chlorides[2]
WESTERN BASIN									
Ontario									
Kingsville	M-1	Lagoon	0.3	3.5	36	45	5	1	14
Leamington	M-2	Primary	2.4	9.4	354	250	64	20	975
Ohio									
Camp Perry	M-9	Secondary	0.16	-	20	5	3	2	8
Port Clinton	M-10	Intermediate S-C	1.45	7.5	177	120	52	13	230
Lakeside	M-11	Intermediate	-	2.9	40	20	3	2	4
TOTAL					627	440	127	38	1,231
CENTRAL BASIN									
Ontario									
Ontario Hospital	M-3	Secondary	0.08	1.0	2	5	10	1	13
Port Stanley	M-4	None	0.15	1.4	25	31	3	1	10
Port Burwell	M-5	None	0.10	.7	14	17	2	0	5
Ohio									
Sandusky	M-12	Primary S-C	5.2	34.2	1,400	800	240	60	520
East Erie Co. SD	M-13	Primary S	0.03	-	600	10	4	9	10
Lorain	M-14	Primary S	10.95	78.5	1,600	1,320	540	150	1,200
Avon Lake	M-15	Intermediate C	1.9	12.3	490	220	80	9	190

Table 3.1.1 (cont'd)

Municipalities	Map index[1]	Existing treatment	Sewage flow (mgd)	Population served with sewers (thousands)	BOD_5	Total solids	Total[2] nitrogen (N)	Total[2] phosphorus (P)	Chlorides[2]
				EASTERN BASIN					
Ontario									
Port Rowan	M-6	None	0.1	.8	14	17	2	0	5
Port Dover	M-7	Primary	0.28	3.2	53	40	14	2	37
Crystal Beach	M-8	Secondary	0.4	2.0	8	7	7	1	28
Pennsylvania									
Erie	M-25	Secondary S-C	40.0	140.0	1,200	640	750	300	2,100
New York									
Ripley	M-26	Primary S	0.1	1.3	570	170	9	4	20
Dunkirk	M-27	Primary S-C	4.3	18.2	1,500	920	130	40	290
Hamburg Twp.	M-28	Primary	1.9	-	270	80	-	20	-
Wanakah	M-29	Primary S	0.25	-	90	50	10	4	30
Mt. Vernon	M-30	Primary S	0.3	-	70	50	30	4	60
TOTAL					3,775	1,974	952	375	2,570
TOTAL FOR LAKE					23,703	17,917	9,413	2,739	24,279

[1]Separate sewer system; C = Combined sewer system; S-C = Separate and combined sewer system.

[2]Estimates based on population served.

Table 3.1.2 Principal industrial waste discharges direct to Lake Erie 1966-67 (short tons/year).

Industries	Map index[1]	Existing treatment	Flow[2] (mgd)	BOD_5	Solids Total	Solids Susp.	Total nitrogen (N).	Total phosphorus (P)	Chlorides
			WESTERN BASIN						
Ontario									
H.J. Heinz Co. of Canada	I-1	Screening	1.1	2,035	4,440	1,020	61	10	237
Michigan									
Enrico Fermi* (Laguna Beach)	I-5		190	-	-	-	-	-	-
Consumer Power (Erie)			385						
Ohio									
Toledo Edison (Toledo)	I-6			-	-	-	-	-	-
			CENTRAL BASIN						
Ontario									
Omstead Fisheries 1961 Ltd. (Wheatley)	I-2	Screening	0.4	467	690	360	35	7	310
Ohio									
U.S. Gypsum (Gypsum)	I-7		0.9	**	600	600			-
Aluminum & Magnesium (Sandusky)	I-8		0.13	**	-	**	-	-	-
TRW (Euclid)	I-9		**	-	**	**	-	-	-
Diamond Shamrock (Painesville)	I-10		10	-	7,880	1,130	130	-	4,470

Table 3.1.2 (cont'd)

Industries	Map index[1]	Existing treatment	Flow[2] (mgd)	BOD_5	Solids Total	Solids Susp.	Total nitrogen (N)	Total phosphorus (P)	Chlorides
Midland Ross IRC (Painsville)	I-11		29	1,590	50,050	3,650	-	-	7,300
Detrex Chemical Ind. Chlorine & Alkali Plant (Ashtabula)	I-12		4.6	-	120	120	-	-	1,800
Union Carbide Linde Div. - Welding Materials Plant	I-13		1.3	-	3,050	140	-	-	-
Union Carbide - Metals Div.	I-14		5.6	-	-	**	-	-	-
Ohio Edison (Lorain)	I-15		121	-	-	**	-	-	-
Cleveland Electric Illuminating (Avon)	I-16		890	-	3,100	3,100			-
Cleveland Electric Illuminating (Cleveland)	I-17		455	-	970	970			-
Cleveland Municipal (Cleveland)	I-18		173	-	-	-			-
Cleveland Electric Illuminating (Eastlake)	I-19		505	-	6,400	6,400			-
Cleveland Electric Illuminating (Ashtabula)	I-20		690	-	220	220			-

Table 3.1.2 (cont'd)

Industries	Map index[1]	Existing treatment	Flow[2] (mgd)	BOD_5	Solids Total	Solids Susp.	Total nitrogen (N)	Total phosphorus (P)	Chlorides
EASTERN BASIN									
*Ontario									
Algoma Steel Corp. (Canadian Furnace Div.)	I-3	None	3.0	27	5,525	1,895			TR
International Nickel Co. of Canada	I-4	Neutralization	0.2	33	36,310	310			TR
Pennsylvania									
Erie Reduction (Erie)	I-21		0.02	2	4	2			-
Hammermill (Erie)	I-22		20	11,300	96,700	15,300			-
Pennsylvania Electric (Erie)	I-23		144	-	34	34			-
New York									
Seneca Westfield Main (Westfield)	I-24		0.5	**	-	**			-
Bethlehem Steel (Lackawanna)	I-25		350	950	63,900				-
Hanna Furnace (Buffalo)	I-26		26	-	-	**			-
Niagara Mohawk	I-27		461		-	-			-
TOTALS FOR LAKE				16,404	279,993	99,151	226	17	14,387

*Intermittent operation.
**Discharge but quantity unknown.
-Data not available.
TR Trace
[1]Map index refers to Fig. 3.2.1 to 3.2.6.
[2]Ontario sources in Imperial gallons; New York sources in U.S. gallons.

Table 3.1.3 Other industrial waste discharges direct to Lake Erie 1966-67 (short tons/year).

Industries	Total iron	Dissolved iron	Sulphate	Sulphite	Ether solubles	COD	Cyanide	Phenols	Other
				WESTERN BASIN					
Ontario									
H.J. Heinz Co. of Canada						-		-	
Michigan									
Enrico Fermi* (Laguna Beach)						-		-	Heat**
Consumer Power (Erie)									Heat 1,472 BTU/hour x 10^6
Ohio									
Toledo Edison (Toledo)						-		-	Heat*
				CENTRAL BASIN					
Ontario									
Omstead Fisheries 1961 Ltd. (Wheatley)						1,350		-	Oil 50
Ohio									
United States Gypsum (Gypsum)						-		-	Heat**
Aluminum and Magnesium (Sandusky)						-		-	Metals**
TRW (Euclid)						-		-	
Diamond Shamrock (Painesville)						-		3	

Table 3.1.3 (cont'd)

Industries	Total iron	Dissolved iron	Sulphate	Sulphite	Ether solubles	COD	Cyanide	Phenols	Other
CENTRAL BASIN (cont'd)									
Midland Ross IRC (Painesville)						-		-	Oil 780 Zinc 1,200 pH 2.3-3.8
Detrex Chemical Ind. Chlorine and Alkali Plant (Ashtabula)						-		-	
Union Carbide Linde Div. - Welding Materials Plant						-		-	Copper 2 pH 0.0-11.0
Union Carbide - Metals Div.						-		-	pH 8.2-12.6
Ohio Edison (Lorain)						-		-	Heat**
Cleveland Electric Illuminating (Avon)						-		-	Heat**
Cleveland Electric Illuminating (Cleveland)						-		-	Heat**
Cleveland Municipal Cleveland									Heat 920
Cleveland Electric Illuminating (Eastlake)						-		-	Heat**
Cleveland Electric Illuminating (Ashtabula)						-		-	Heat**
EASTERN BASIN									
Ontario									
Algoma Steel Corp. (Canadian Furnace Div.)	2,830					365		-	Calcium 530

Table 3.1.3 (cont'd)

Industries	Total iron	Dissolved iron	Sulphate	Sulphite	Ether solubles	COD	Cyanide	Phenols	Other
EASTERN BASIN (cont'd)									
International Nickel Co. of Canada						1,240	0.3	-	Nickel 105 Calcium 1390 Copper 18
Pennsylvania									
Erie Reduction (Erie)			9,300			-		-	
Hammermill (Erie)						-		-	
Pennsylvania Electric (Erie)						-		-	Heat 720
New York									
Seneca Westfield Main (Westfield)						-		-	
Bethlehem Steel (Lackawanna)						2,010	170	120	pH 4.0-7.0 Heat** Oil 5,650
Hanna Furnace (Buffalo)						-		-	Heat** Oil**
Niagara Mohawk						-		-	Heat 2,200
TOTALS FOR LAKE	2,830		9,300			4,965	170.3	123	

*Intermittent operation.
**Discharged but quantity unknown.
-Data not available.

immediate effects of local pollution problems are compounded. Each tributary contributes its incremental nutrient load, the magnitude of which varies with the extent of the municipal, industrial and agricultural development and with the size of the respective drainage basin.

Some major tributaries contain large quantities of municipal and industrial wastes which are discharged into the streams very near their mouths. For example, Toledo's municipal waste treatment plant effluent is discharged into the Maumee River only a few hundred feet upstream of the mouth. Similarly, Detroit and Windsor discharge into the Detroit River and one of Cleveland's three sewage treatment plants discharges into the Cuyahoga River.

Table 3.1.4 lists the major tributaries to Lake Erie. The estimated quantities of waste discharged are based on analysis of stream waters and concurrent flow data. As this Table shows, the Detroit River is by far the largest contributor for most constituents. The Detroit metropolitan area is responsible for a large portion of this waste input. The Maumee River is the largest source of suspended solids, accounting for more than 40 percent (2 million short tons/year) of the total tributary inputs. This reflects a large eroded sediment load.

The Detroit River contains the Lake Huron outflow plus municipal and industrial wastes and tributary drainage discharged to the St. Clair-Detroit River system. The Maumee River is polluted by agricultural runoff and municipal wastes; the Sandusky by agricultural runoff, food processing industries, and municipal wastes, and the Cuyahoga by municipal and industrial wastes. The Grand River of Ontario, receiving both municipal and industrial wastes, is the largest source of waste materials discharging into Lake Erie from Canada.

Table 3.1.5 lists the nutrient sources for major United States and Ontario tributaries. Quantities shown under the heading "Other Sources" include contributions from agricultural drainage, eroded sediments, animal wastes and natural sources. Data for the past five years indicate a progressive increase in the amount of nutrients applied, although the number of acres fertilized has decreased slightly. The figures are reported as total nitrogen and phosphorus, and do not differentiate between the chemical forms of the fertilizers as applied to the soils. A comparison can be made of the amounts of phosphorus discharged by tributaries to Lake Erie in Table 3.1.5.

Table 3.1.4 Tributary waste discharges to Lake Erie 1966-67 (short tons/year).

Tributaries	Flow (cfs)	Population served with sewers (thousands)	BOD_5	Solids Total	Solids Susp.	Total nitrogen (N)	Total phosphorus (P)	Chlorides
WESTERN BASIN								
Ontario - Michigan								
Detroit River **			91,000	30,600,000	1,600,000	126,000	17,600	3,300,000
Michigan								
Huron River			400	74,800	1,800	300	430	18,000
Raisin River			500	95,700	4,700	700	346	26,000
Ohio								
Maumee River			20,000	3,400,000	2,000,000	12,000	2,687	130,000
Portage River			700	114,400	27,400	500	164	6,000
TOTAL			112,600	34,284,900	3,633,900	139,500	21,227	3,480,000
CENTRAL BASIN								
Ontario								
Kettle Creek	160*	21.0	1,210	71,327	5,890	1,380	31	9,080
Catfish Creek	142*	4.5	350	56,586	5,858	175	23	2,786
Big Otter Creek	264	7.2	1,900	346,700	33,700	1,100	102	2,200
Ohio								
Sandusky River			5,700	600,000	150,000	7,300	567	32,000
Huron River			400	156,000	46,000	400	134	5,300
Vermilion River			200	90,000	17,000	300	70	4,400
Black River			700	81,000	15,000	1,000	269	8,100
Rocky River			1,400	160,000	30,000	1,000	260	21,000
Cuyahoga River			8,900	509,000	89,000	4,600	2,600	79,000

Table 3.1.4 (cont'd)

Tributaries	Flow (cfs)	Population served with sewers (thousands)	BOD_5	Solids Total	Solids Susp.	Total nitrogen (N)	Total phosphorus (P)	Chlorides
Chagrin River			500	125,000	35,000	200	148	4,800
Grand River			1,300	1,510,000	210,000	800	104	680,000
Ashtabula River			200	24,600	4,600	100	14	2,800
Conneaut Creek			400	45,100	9,100	100	36	5,700
TOTAL			23,160	3,775,313	651,148	18,455	4,358	857,166
EASTERN BASIN								
Ontario								
Big Creek	209	3.6	200	53,600	2,600	160	9	2,500
Dedrick Creek	29.6	0	40	4,600	500	20	2	90
Lynn River	104*	8.7	260	23,200	1,200	160	11	1,000
Nanticoke Creek	56*	1.3	280	14,400	500	60	4	150
Sandusk Creek	46*	1.6	60	9,200	700	70	6	140
Grand River	1,820*	278	3,900	448,000	32,000	1,710	1,306	32,600
New York								
Cattaraugus Creek			6,000	370,000	140,000	2,700	101	17,000
Buffalo River and small tributaries			13,000	434,000	74,000	5,000	318	59,000
TOTAL			23,720	1,357,000	251,500	9,880	1,757	112,480
LAKE ERIE TOTALS			159,480	39,417,213	4,536,548	167,835	27,342	4,449,646

*Estimated
**Includes Lake Huron outflow.

Table 3.1.5 Tributary nitrogen and phosphorus discharges to Lake Erie (short tons/year)

	Municipal waste		Industrial waste		Other sources		Total sources	
	Nitrogen	Phosphorus	Nitrogen	Phosphorus	Nitrogen	Phosphorus	Nitrogen	Phosphorus
Western basin								
Ontario-Michigan								
Detroit River	21,260	11,510	6,700	980	98,040*	5,110**	126,000*	17,600**
Michigan								
Huron River	-	245	-	18	-	167	300	430
Raisin River	-	146	-	18	-	182	700	346
Ohio								
Maumee River	-	1,408	-	182	-	1,097	12,000	2,687
Portage River	-	73	-	4	-	87	500	164
Basin total		13,382		1,202		6,643**	139,500*	21,227**
Central basin								
Ontario								
Kettle Creek	50	30	0	1	1,330	0	1,380	31
Catfish Creek	11	3	5	4	159	16	175	23
Big Otter Creek	34	12	0	0	1,066	90	1,100	102
Ohio								
Sandusky River	-	128	-	5	-	434	7,300	567
Huron River	-	55	-	2	-	77	400	134
Vermilion River	-	9	-	2	-	59	300	70
Black River	-	128	-	9	-	132	1,000	269
Rocky River	-	128	-	7	-	125	1,000	260

Table 3.1.5 (cont'd)

	Municipal waste		Industrial waste		Other sources		Total sources	
	Nitrogen	Phosphorus	Nitrogen	Phosphorus	Nitrogen	Phosphorus	Nitrogen	Phosphorus
Ohio (cont'd)								
Cuyahoga River	-	1,700	-	274	-	626	4,600	2,600
Chagrin River	-	36	-	2	-	110	200	148
Grand River	-	46	-	7	-	51	800	104
Ashtabula River	-	0	-	9	-	5	100	14
Conneaut Cr.	-	21	-	2	-	13	100	36
Basin total		2,296		324		1,738	18,455	4,358
Eastern basin								
Ontario								
Big Creek	16	6	0	3	144	0	160	9
Dedrich Creek	0	1	0	0	20	1	20	2
Lynn River	29	11	0	0	131	0	160	11
Nanticoke Creek	6	3	0	0	54	1	60	4
Sandusk Creek	7	3	0	0	63	3	70	6
Grand River	1,215	408	495	458	0	440	1,710	1,306
New York								
Cattaraugus Creek	-	18	-	9	-	74	2,700	101
Buffalo River	-	123	-	10	-	67	5,000	200
Small tributaries	-	100	-	-	-	18	-	118
Basin total		673		480		604	9,880	1,757
Lake total		16,351		2,006		8,985**	167,835*	27,342**

*Includes 66,000 short tons/year in Lake Huron outflow
**Includes 2,240 short tons/year in Lake Huron outflow

The regions that are primarily agricultural contribute significant nutrient loads through land drainage. On the basis of the data in Table 3.1.5, 91 percent of the total municipal waste phosphorus discharged by tributaries to Lake Erie comes from the Detroit, Maumee, and Cuyahoga Rivers. Considering all tributary sources of phosphorus (municipal, industrial and other), these three rivers account for 83 percent of the total tributary input, with 64 percent contributed by the Detroit River. The Grand River in Ontario contributes 5 percent of the phosphorus, leaving about 14 percent from all other tributaries.

Table 3.1.6 indicates the relative magnitude of municipal, industrial, and other sources of phosphorus and nitrogen. It may be seen from this Table that 63 percent of the phosphorus inputs from all sources comes from municipal wastes. Nitrogen data are complete only for the Detroit River, but the relative importance of land runoff as a source is clearly indicated, since the Lake Huron contribution can be attributed largely to that source.

3.1.4 <u>Other Sources</u>

Vessel Wastes

The Lake Erie basin is within the commercial sphere of one of the most industrially productive areas in the world. The availability of the lakes for waterborne traffic has promoted the development of a number of major harbours principally in the United States. The construction of the St. Lawrence Seaway has resulted in a large volume of overseas traffic, with many vessels of foreign registry entering the lakes each year.

Vessel wastes, such as sanitary sewage, bunker oil, garbage, bilge water, ballast and dunnage, damage water quality especially if wasted in harbour areas. Harbours do not normally have facilities for collecting or treating wastes from vessels or from stevedore activities. The effects of vessel wastes may include oxygen depletion, bacterial contamination, and impaired aesthetics caused by floating oil, garbage and debris. The domestic waste load from commercial vessels operating in Lake Erie is equivalent to the contribution of 1,200 persons per day during the eight month navigation season. Many larger vessels are being equipped with self-contained treatment systems for sanitary sewage. However, discharges of oil continue to be a serious problem, both in harbours and along the shipping lanes.

Table 3.1.6 Total phosphorus and total nitrogen to Lake Erie by source (percent).

	Detroit R.	Maumee R.	Cuyahoga R.	Other tribs.	Direct discharge	Total
			Total phosphorus			
Municipal	38	5	6	5	9	63
Industrial	3	1	1	2	0	7
Runoff	10	3	2	8	0	23
Lake Huron	7	0	0	0	0	7
Totals	58	9	9	15	9	100*
			Total nitrogen			
Municipal	12	-	-	-	5	-
Industrial	4	-	-	-	0	-
Runoff	18	-	-	-	0	-
Lake Huron	37	0	0	0	0	37
Totals	71	7	3	14	5	100*

- Data not available

* Does not include atmospheric sources

The tremendous increase in pleasure craft over the past few years has given rise to concern for their effect on water quality. The problem is most severe in harbour and marina areas, where waste disposal facilities are usually not available. Growing provincial and state concern is leading to control measures. Ontario, New York, and Michigan have laws prohibiting discharge and requiring treatment facilities on larger pleasure craft. The annual waste contribution to Lake Erie from pleasure craft is equivalent to the raw sewage of a permanent population of 5,500.

Dredging

Dredging in Canadian waters of the Great Lakes is a responsibility of the Canada Department of Public Works. Generally dredging is done on a contract basis with the contractor being required to dispose of dredged spoils in water no less than 15 metres, nor within three miles of the dredging site. An exception is made to this rule in certain shallow areas of Lake Erie, where spoil areas are located approximately two to three miles from the dredging site, and the contractor is required to ensure that a minimum of nine metres of water remain above the spoil after deposition. In certain instances dredged spoils are used to reclaim land and are being deposited behind retaining walls. Estimated quantities dredged in 1968 are shown on Table 3.1.7.

In addition to dredging contracted for by the Canada Department of Public Works, the National Harbours Board maintains facilities at Port Colborne where dredging has proved necessary. The most recent dredging operation at this location occurred in 1963, when 5,000 cubic yards of material were removed. The contractor was permitted to dispose of material either on the side of the Quarantine Dock, or in the Lake Erie dumping ground located approximately 3 miles from the site of the work.

OWRC and the Canada Department of Public Works have initiated studies of the character of dredged material and its effect on water quality in the disposal areas.

Maintenance of authorized navigation depths in federal harbour projects on the United States shore is the responsibility of the Corps of Engineers, U.S. Army. Dredging is done either with government owned equipment or by contract. Disposal of material from most of the harbours is by dumping at locations designated by the Corps of Engineers, usually a few miles off shore. At Detroit, material from the Rouge River is deposited in a dyked disposal area on Grassy Island in the Detroit River. At Toledo, material from the Maumee River and

Table 3.1.7 Sediment loads (cubic yards) to Lake Erie from dredging operations, 1968.

Harbour	Quantity cubic yards
Canada	
Port Burwell	11,000
Port Stanley	113,000
Erieau	22,000
Sturgeon Creek	Not available
Port Dover	44,000
Leamington	16,000
United States	
Ashtabula, Ohio	345,000
Buffalo, New York	125,000
Cleveland, Ohio	725,000
Conneaut, Ohio	190,000
Dunkirk, New York	25,000
Erie, Pennsylvania	200,000
Fairport, Ohio	390,000
Huron, Ohio	300,000
Lorain, Ohio	444,000
Monroe, Michigan	300,000
Sandusky, Ohio	650,000
Toledo, Ohio	1,000,000

inner harbour areas is deposited in dyked disposal areas in Maumee Bay. At Cleveland, material from the Cuyahoga River was placed in a dyked disposal area in Cleveland Harbour in 1968. At Buffalo, material from the Buffalo River is deposited in a dyked disposal area in the harbour.

Private slips and docking facilities outside federal dredged areas are maintained by the property owners under permits issued by the Corps of Engineers. Disposal of materials is usually in designated lake areas.

In most of the United States Lake Erie harbours, the bottom sediments consist of a combination of silt and municipal and industrial wastes. Some of these sediments contain high concentrations of pollutants such as compounds of iron and other metals, oil and grease, nutrients, and oxygen-consuming materials. The transfer of these materials to the open lake environment constitutes a source of pollution.

On the basis of studies carried out by FWPCA, it is estimated that 660,000 short tons of solids (dry weight) were transported from Cleveland Harbour to Lake Erie during the period January 7, 1966 to January 7, 1967. These solids exerted a total chemical oxygen demand of 119,000 short tons, and a total BOD_5 of 8,100 short tons. Estimated quantities of several constituents transported to the lake are given in Table 3.1.8.

Table 3.1.8 Estimated quantities transported to Lake Erie from Cleveland harbour dredging (short tons) (After U.S. Corps of Engineers, 1969).

Constituent	River	Harbour	Total
Volatile solids	58,000	13,000	71,000
Oil and grease	16,000	1,600	17,600
Phosphorus	1,860	300	2,160
Nitrogen	2,300	320	2,620
Iron	51,000	9,000	60,000
Silica	270,000	149,000	419,000
Total dry solids	460,000	200,000	660,000

Oil and Gas Drilling

Offshore drilling could cause significant pollution problems in Lake Erie. Potential sources of pollution include oil, brine and other wastes associated with the drilling process. If considerable quantities of oil are encountered in drilling, the risk of oil pollution will be high and could lead to serious problems. Presently, most drilling in Lake Erie is for gas; however, with the recent discovery of oil, it seems that oil drilling is a possibility.

All producing wells are located in Canadian waters. Drilling was begun in Canada in 1913, but no significant production was achieved until 1940. At the end of 1966, there were 221 active wells and 60 capped wells in the Canadian section of the lake. These wells produced a total of 4,447 million cubic feet of gas in 1966 (Ontario Department of Energy and Resources Management, 1969). This represented 29 percent of the total Ontario production. In 1967, 21 new wells were drilled in Lake Erie, of which seven were producers (Ontario Department of Energy and Resources Management, 1967).

All underwater exploration in Canada is undertaken on leased crown land and no drilling is permitted within 2,000 feet of shore. Wells are inspected by the Ontario Department of Energy and Resources Management to ensure freedom from pollution.

Although a few wells were drilled in United States waters in past years there has been no production to date. The states of New York and Ohio are considering leasing underwater lands for drilling. Thus far only Pennsylvania has commenced to lease underwater lands. The Ohio program has been postponed indefinitely as a result of criticism regarding pollution potential. Michigan has adopted a policy of not granting oil and gas leases on underwater lands in the Great Lakes and connecting waters. New York State's plan for oil and gas exploration is not fully developed.

Sediments

The lake bottom is a repository for the materials which settle out of the overlying waters. Contaminated sediments result from pollution of the overlying waters. Pollution of the water by the sediments is usually considered insignificant, in many lakes. However, in Lake Erie the bottom sediments are noticeably affecting overlying water quality.

Sediment resuspension causes an increase in turbidity, a decrease in dissolved oxygen and an increase in dissolved and particulate nutrient content. The shallow western basin waters are frequently mixed from top to bottom and here the effects of resuspension are greatest.

In the deep central basin, stirring of the bottom sediments is much less pronounced. Chemical activity of the sediment-water interface is important however, particularly during summer in the oxygen-depleted hypolimnion. The exchange at this time results in significant quantities of phosphorus, nitrogen, carbon dioxide, iron, manganese and sulphides being released to the overlying waters. FWPCA (1968) found that during summer stagnation periods, the waters of the central basin hypolimnion averaged 50 percent higher in ammonia, 33 percent higher in organic nitrogen, 70 percent higher in nitrate, 60 percent higher in total phosphorus, 7 percent higher in alkalinity, 5 percent higher in conductivity, 11 percent higher in total solids, and 72 percent higher in silica than those of the epilimnion. Potos (1968) made a comprehensive study of a Cleveland water intake during stratification periods and found that 88 percent more iron and 86 percent more manganese occurred in the hypolimnion than in the epilimnion.

In the eastern basin, the contribution of bottom sediments to the degradation of the overlying water is probably not significant, since resuspension and interfacial chemical exchange are minimal.

Atmosphere

Atmospheric sources of nutrients are the contribution of nitrogen compounds from rainfall, dustfall and fixation of nitrogen by algae. Atmospheric sources contribute less than 10 percent of the total nitrogen supply to Lake Erie. According to Hutchinson (1954), it is reasonable to conclude that the greater part of the nitrate contained in rain is not derived from direct oxidation of nitrogen in the atmosphere. Photochemical oxidation of ammonia is apparently the more reasonable explanation for the source of nitrate in rainwater (Feth, 1966). Junge and Manson (1961) emphasized the abundance of ammonium-bearing particles in atmospheric aerosols, based on studies of samples near the earth's surface. Studies of particulate matter of the stratosphere revealed that the aerosols consist largely of ammonium sulphate and ammonium persulphate. It is suggested that a constant fallout of these particles occurs from the stratosphere to lower layers of the atmosphere, where they are incorporated into falling rain and snow.

Some of the nitrogen found in rainwater could be attributed to industrial activity, and in certain locations to smog. Gambell and Fisher (1964) have studied individual rainfalls in the United States and have concluded that NH_4 and NO_3 ions in rain resulted mostly from gaseous constituents of the atmosphere. Industrial air pollutants contain ammonia and other gaseous nitrogen compounds.

To give an indication of the amount of nitrogen expected to reach Lake Erie, quantitative results of observations have been cited and used for quantity estimates.

The nitrogen content of rain and snow was studied at Ottawa from 1907 to 1924 (Shutt and Hedley, 1925). In these studies nitrogen was determined as free ammonia, as albuminoid nitrogen or nitrate plus nitrite. On the average, nitrogen as nitrate plus nitrite made up about 30 percent of the total nitrogen in rain and about 35 percent of the total nitrogen in snow. Rain contributed about 83 percent and snow 17 percent of the precipitated nitrogen during the 17 year observation period. The total nitrogen contributed to the land averaged about 7 lbs/acre/year.

Studies on inorganic nitrogen in precipitation and dust fallout were carried out at Hamilton, Ontario, over a period of 18 months. The results were reported by Matheson (1951). The nitrogen fall for the whole period averaged 5.8 lbs/acre/year. Sixty-one percent of the total nitrogen was collected on 25 percent of the days, when precipitation occurred. The balance occurring on days without precipitation, was attributed to the sedimentation of dust. Ammonia nitrogen averaged 56 percent of the total. In comparison, McKee (1962) reported a rate of 2 to 10 kilograms per hectare per year (1.8 to 8.9 lbs/acre/year) from European studies on atmospheric nitrogen, precipitation and dustfall.

Based on an average value of 5 lbs/acre/year of total nitrogen, which appears to be justified from actual observations, 16,000 tons N/year could be expected to fall on Lake Erie. This is about 8 percent of the nitrogen input from all sources.

Molecular nitrogen (N_2) is present in lake waters near the concentrations corresponding to equilibrium with air. The ability of certain species of algae (especially blue-greens) and bacteria to utilize molecular nitrogen as a nutrient source has been well-documented (Dugdale *et al.*, 1959; Fogg, 1956; Williams and Burris, 1952) and is referred to as nitrogen fixation. The actual quantity of nitrogen input into Lake Erie via nitrogen fixation cannot be estimated because of the lack of data.

An indication of the relative importance of nitrogen fixation can be obtained from some quantitative work done on Sanctuary Lake in Pennsylvania (Dugdale and Dugdale, 1962) and Lake Mendota in Wisconsin (Goering and Neess, 1964). During the period of maximum nitrogen fixation rates, from about June to August, nitrogen fixation accounted for one to three percent of the total organic nitrogen present in the surface waters of Sanctuary Lake and 0.1 to 0.6 percent in the case of Lake Mendota. Both lakes have large blooms of blue-green algae, regularly, and probably represent more extreme cases of nitrogen fixation than either Lake Ontario or Lake Erie. In all probability, nitrogen fixation can be discounted as a significant source of nitrogen in the lower Great Lakes.

3.2 IMMEDIATE EFFECTS

3.2.1 Effects on Water Quality

Inadequately treated municipal and industrial wastes together with tributary discharges enter the lake at many locations (Fig. 3.1.1 and Fig. 3.2.1 to 3.2.6). One of the most significant effects of this pollution is the damage to recreational use in the more densely populated areas. Beaches are often littered with debris, nutrient-stimulated algae and dead fish.

Bacterial contamination associated with waste inputs is a direct health hazard and has resulted in many miles of polluted beaches especially near the large metropolitan areas. The shoreline of bathing beaches in the Detroit River below the Rouge River mouth and along the lake near Toledo and Cleveland, are usually unfit for swimming. In these areas, coliform concentrations may run as high as a million or more organisms/100 ml, many times greater than safe levels. A satisfactory level is usually considered to be 1,000 organisms/100 ml or less. Of the 51 beaches on the United States side for which reliable data are available, 29 are considered acceptable, 11 are questionable and 11 are unacceptable for swimming. Notable among the acceptable beaches are East Harbour State Park, Cedar Point, Headlands State Park, Presque Isle, and Evangola State Park. The Ontario shore waters of the western basin for a distance of 10 miles east of the Detroit River are often unfit for body contact recreation. Elsewhere, the bacterial quality along the north shore is acceptable with the exception of several locations where water quality problems are localized.

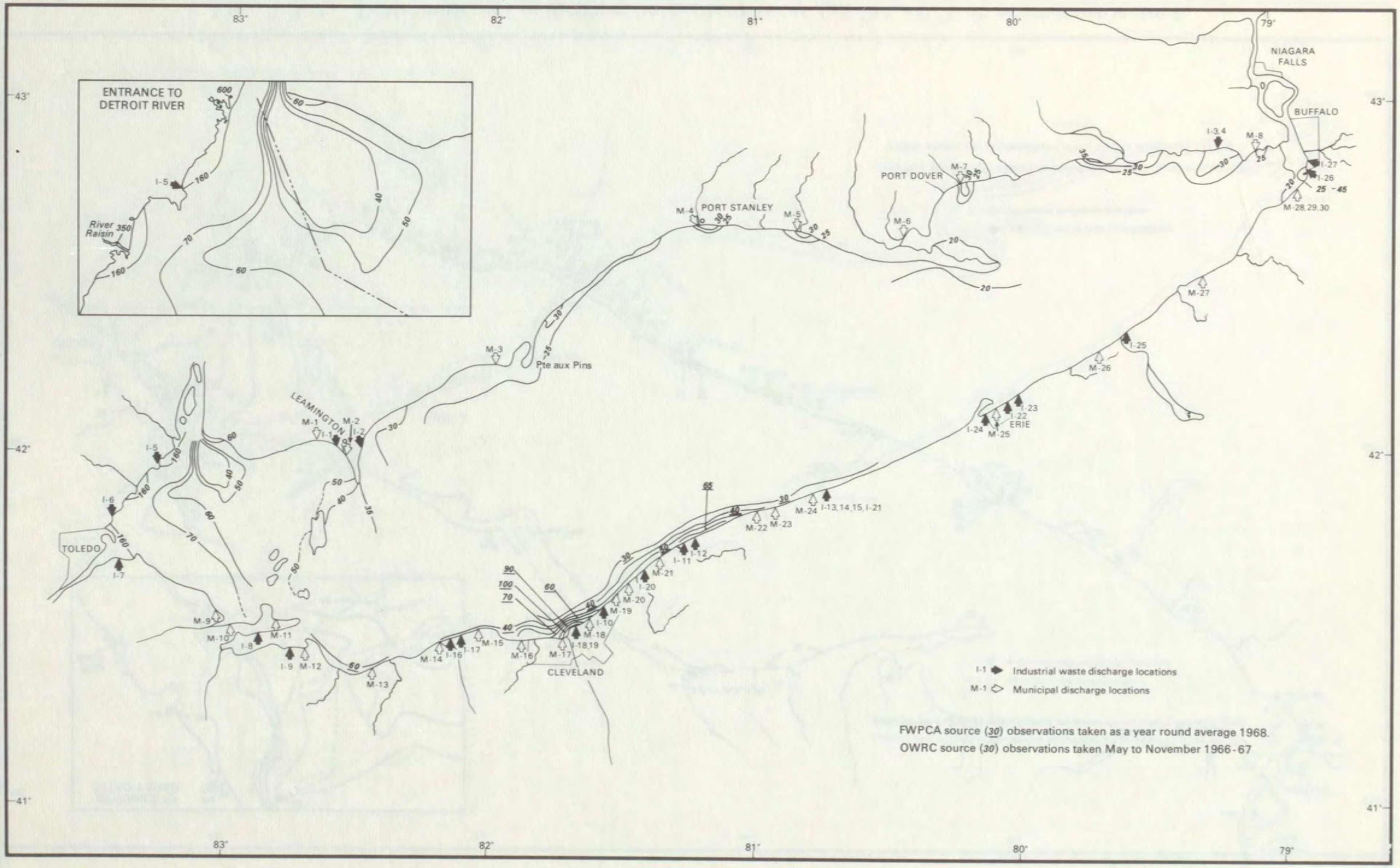

Fig. 3.2.1 Distribution of total phosphorus (μg total-P/1) in nearshore waters.

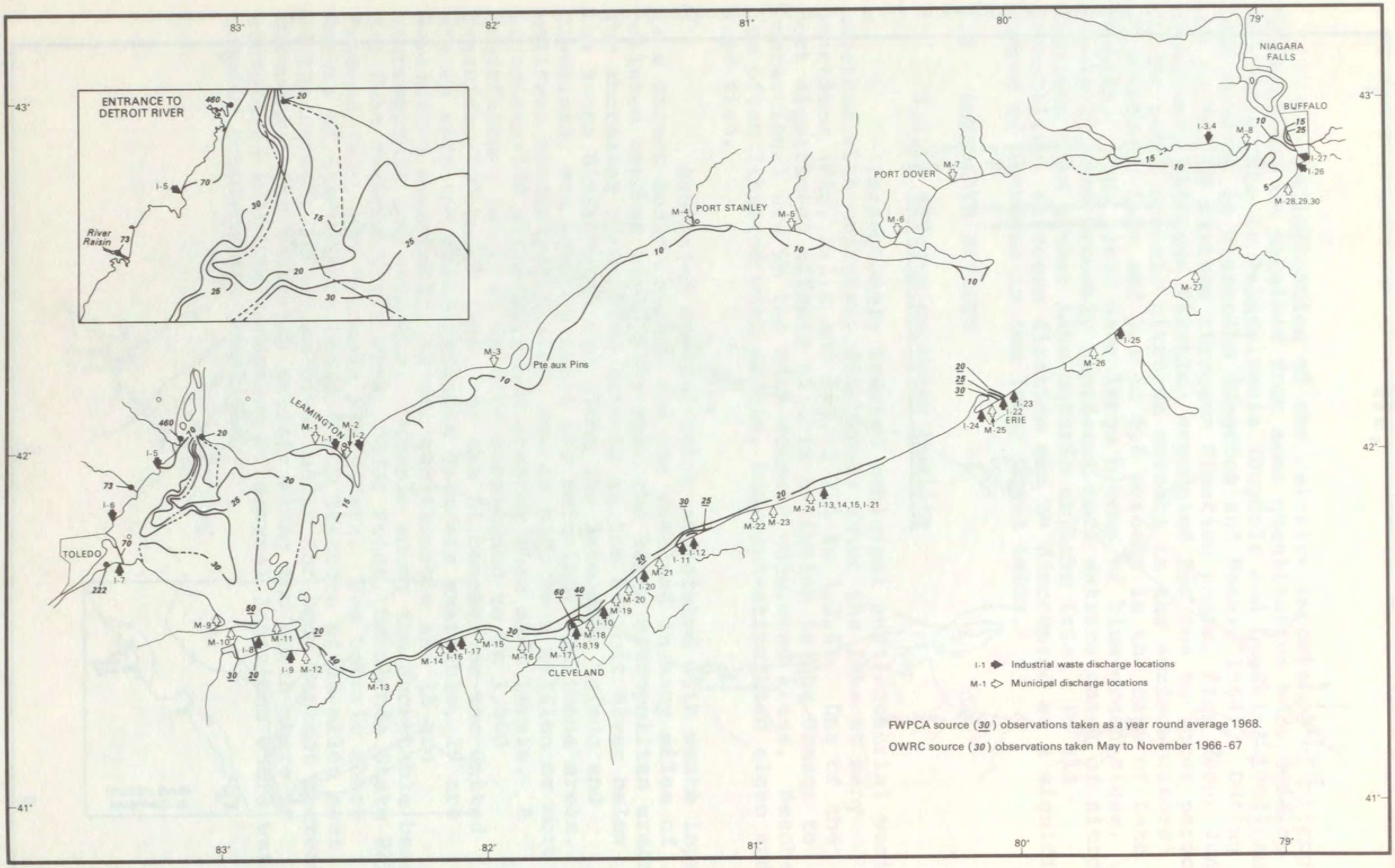

Fig. 3.2.2 Distribution of orthophosphate-phosphorus ($\mu g\ PO_4$-P/1) in nearshore waters.

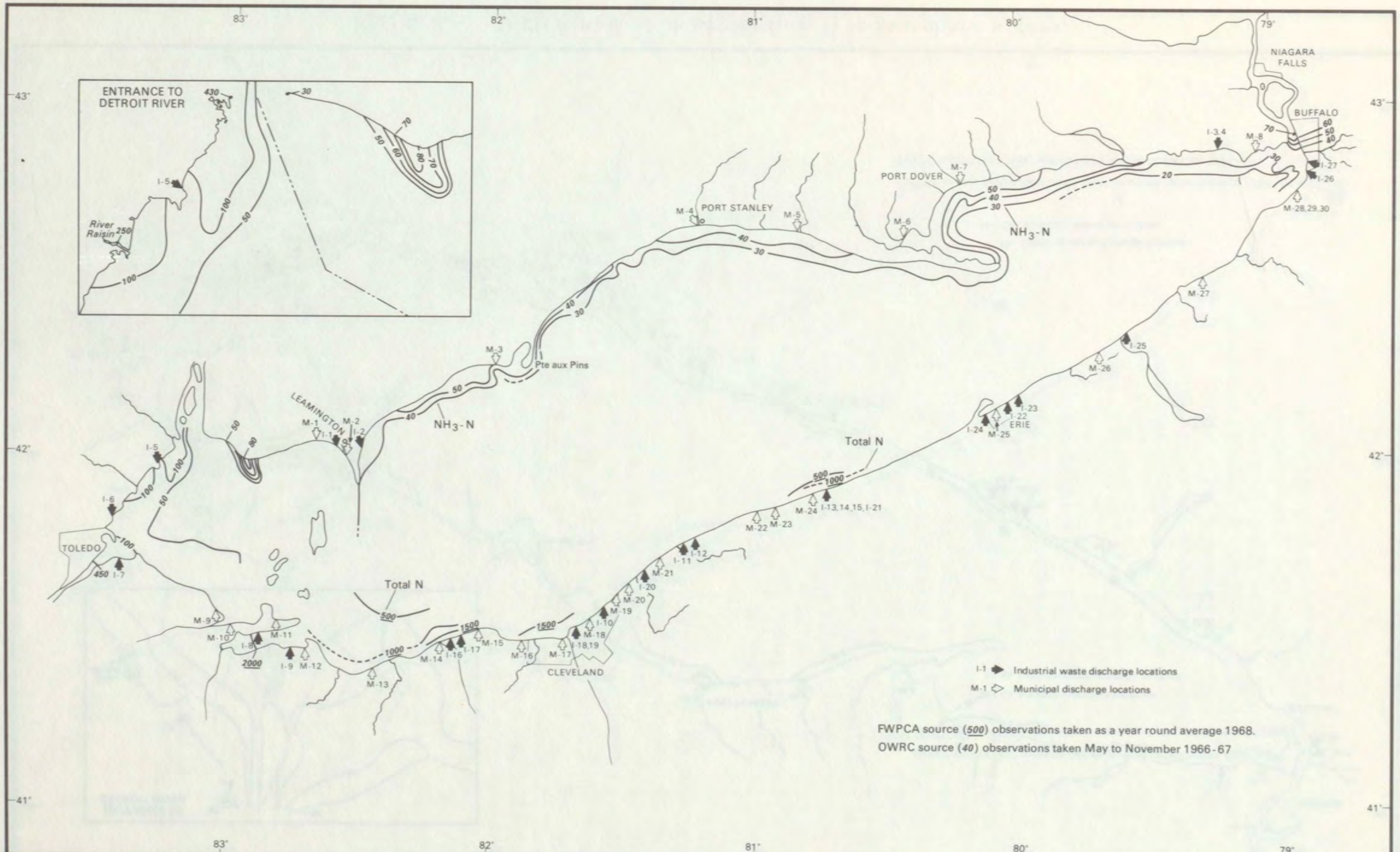

Fig. 3.2.3 Distribution of ammonia-nitrogen (NH_3-N) and total nitrogen (μg N/1) in nearshore waters.

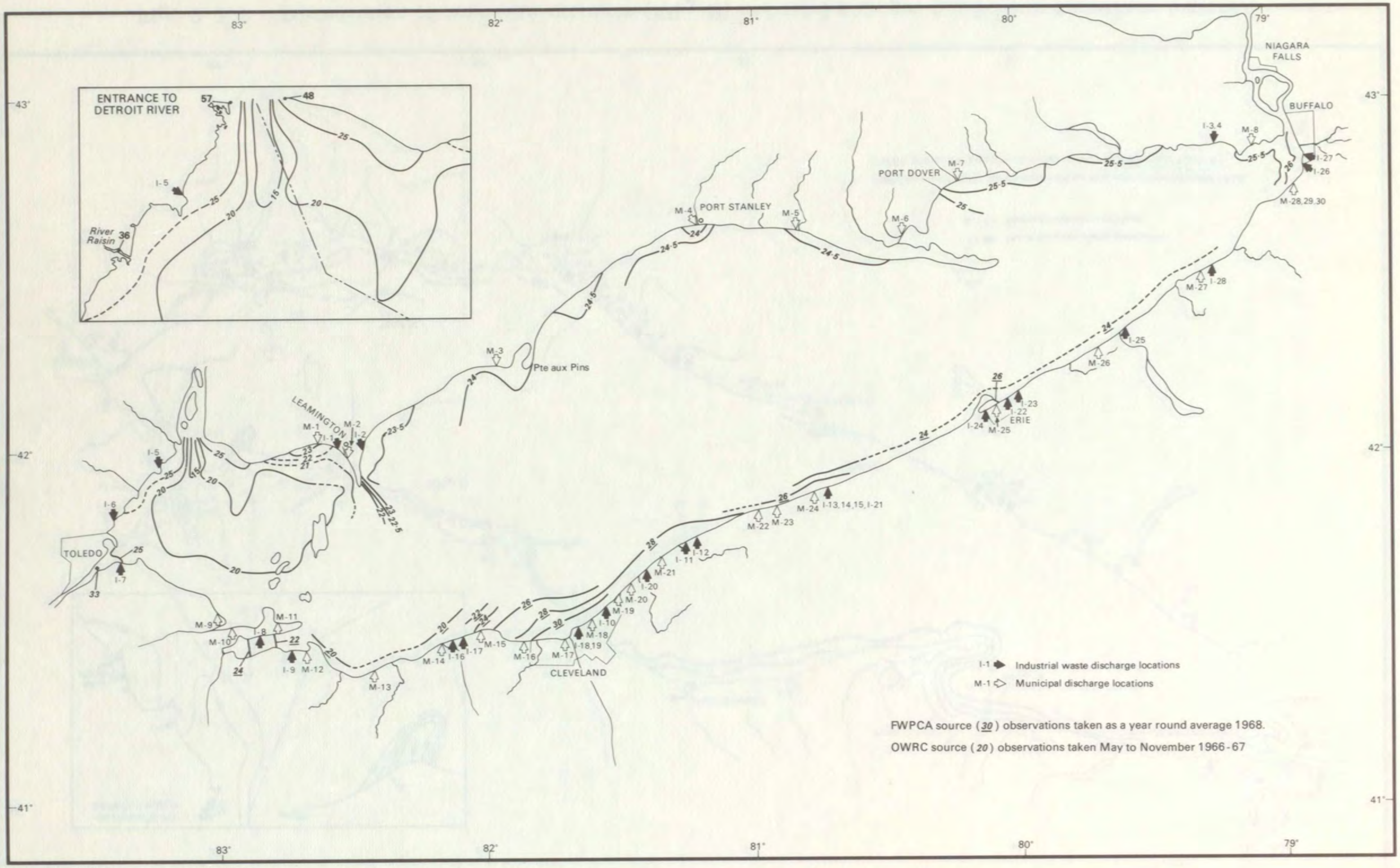

Fig. 3. 2. 4 Distribution of chlorides (mg/1) in nearshore waters.

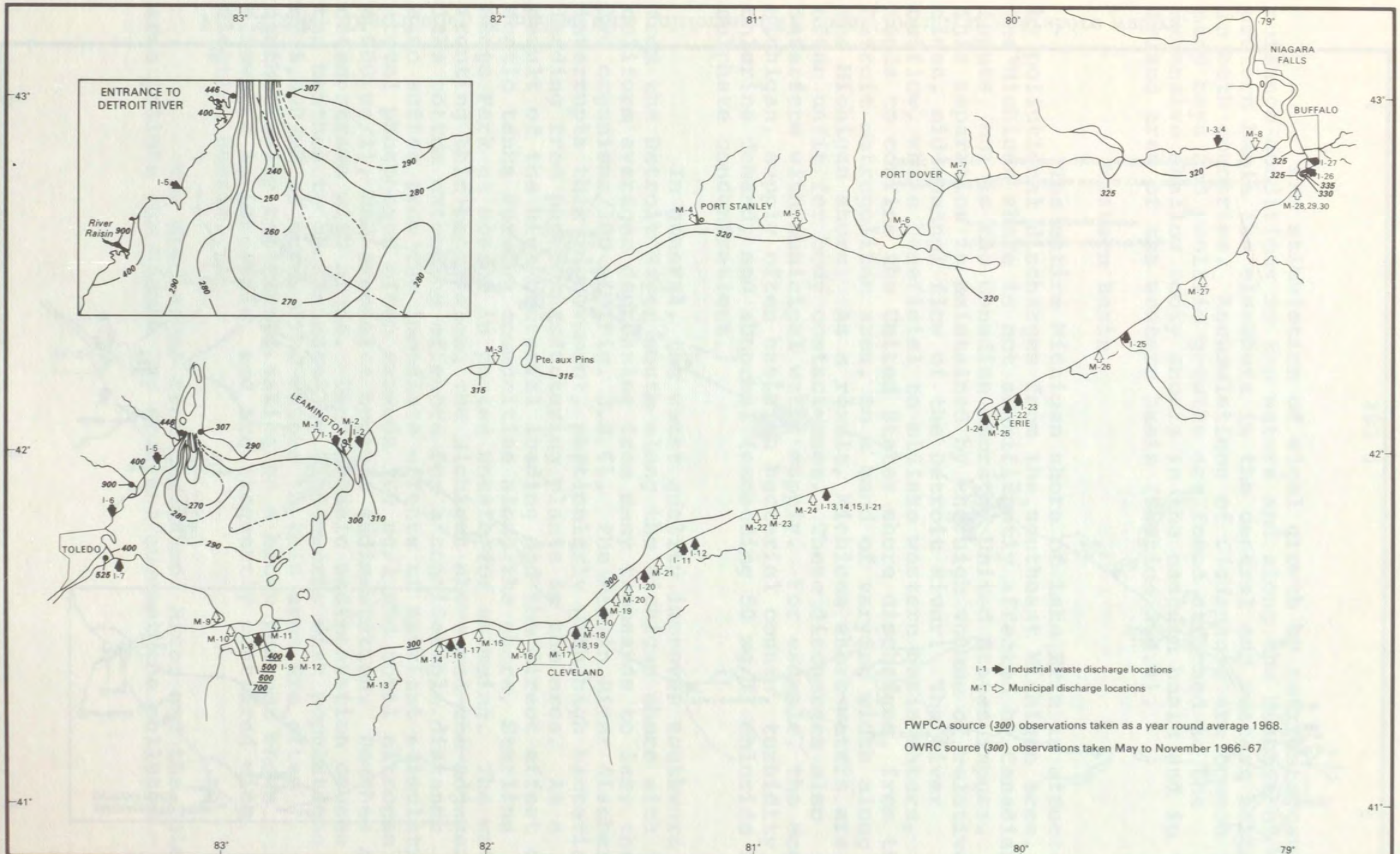

Fig. 3.2.5 Distribution of conductivity (μmhos/cm at 25°C) in nearshore waters.

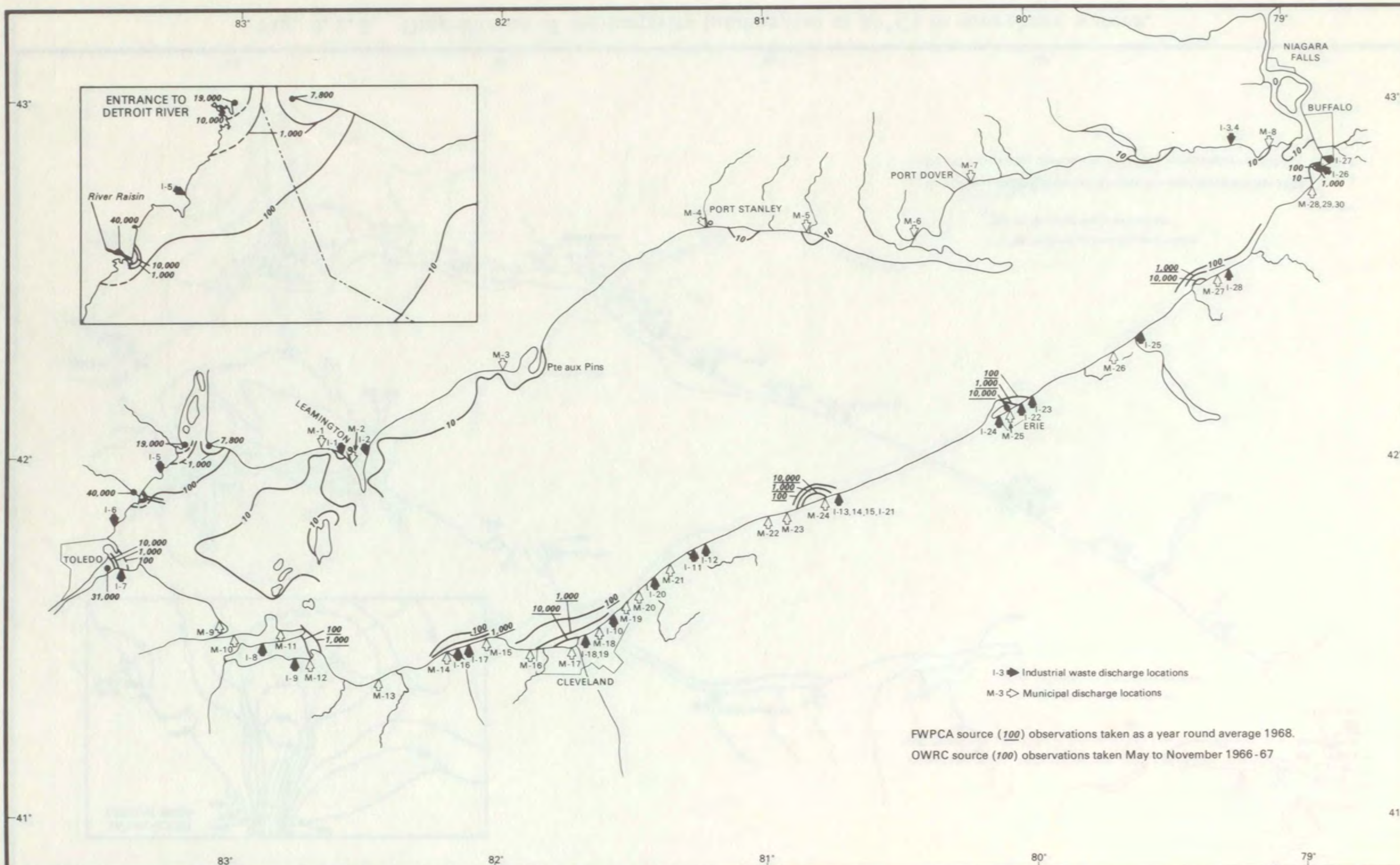

Fig. 3.2.6 Distribution of median total coliforms (MF count/100 ml) in nearshore waters.

The stimulation of algal growth by nutrients causes nuisance conditions in the waters and along the beaches of the western basin and elsewhere in the central and western basins in both countries. Accumulations of *Cladophora* are common in many bays and prolific growths are found attached to the extensive shallow rocky shoals in the eastern basin and in the island area of the western basin (Section 2.4.1).

Western Basin

The entire Michigan shore of Lake Erie is affected by pollutional discharges from the southeast Michigan area. The Michigan shore is not significantly affected by Canadian inputs, nor is the Canadian shore by United States inputs. This separation is maintained by the high volume of relatively clean, mid-channel flow of the Detroit River. The river outflow, while beneficial to midlake western basin waters, tends to confine the United States shore discharges, from the Detroit metropolitan area, to a band of varying width along the Michigan shore. As a result, Michigan shore waters are often unfit for body contact uses. These discharges also interfere with municipal water supply. For example, the Monroe, Michigan, supply often has high bacterial counts, turbidity, chlorine demand, and abnormal (exceeding 50 mg/l) chloride and sulphate concentrations.

In general, the water quality improves southward from the Detroit River mouth along the Michigan shore with coliform averages decreasing from many thousands to less than 100 organisms/100 ml (Fig. 3.2.6). The Raisin River discharge interrupts this improvement, particularly with high bacterial loading from paper manufacturing plants in the area. As a result of the high bacterial loading and the direct affect of septic tanks serving communities along the shore, Sterling State Park at Monroe is posted unsafe for swimming. The waters fronting this beach along the Michigan shore and the adjacent lake bottom extending offshore for a considerable distance also suffer from the immediate effects of nutrient stimulation (total phosphorus often exceeds 100 µg/l and total nitrogen 4,000 µg/l), and excessive organic sedimentation. Beaches are often strewn with algae. High organic sedimentation causes the benthos to be dominated by sludgeworms with populations of 5,000/m^2 or more. The waters in this area are often aesthetically repugnant, taking on a brown hue not shown elsewhere in Lake Erie, and are frequently cluttered with floating debris.

The discharges from the Maumee River and the Toledo area pollute the Maumee Bay area and augment the polluted waters flowing south along the Michigan shore. Bacterial concentrations in Maumee Bay frequently cause conditions hazardous to health (10,000 or more coliforms/100 ml), largely originating in Toledo from sewage treatment plant effluent, combined sewer overflow, and treatment plant by-passing. The bay is discoloured by the silt-laden river, shore erosion and industrial and municipal wastes. The Maumee River also discharges considerable quantities of nutrients from agricultural and municipal sources. The highest phosphorus and nitrogen concentrations of any Lake Erie water can be found in Maumee Bay and the Michigan waters of Lake Erie (Fig. 3.2.1, 3.2.3).

The effect of Michigan and Maumee basin inputs is felt as far east as the Toledo water intake, 12 miles east of the river mouth and two miles offshore. The water supply is treated frequently for excessive turbidity, hardness, bacteria, algae, and tastes and odours.

The beaches between Maumee Bay and Port Clinton have occasional bacterial and algal problems but generally, the nearshore water is of reasonably satisfactory quality with the exception that turbidity is frequently high.

At Port Clinton, the waters fronting the city are excessively enriched and occasionally contaminated. The nearshore water quality from Port Clinton to Marblehead and around the islands suffers from nutritional over-enrichment, with the luxuriant production of the attached alga *Cladophora*.

Water quality problems along the Canadian shoreline for a distance of 10 miles eastward from the Detroit River can be traced to pollutants discharged in the Windsor-Amherstburg area. These waters are often unfit for body contact recreation. Coliform values in excess of 2,000/100 ml were prevalent along the beach during the 1966 bathing season. Extensive bacterial contamination also occurs at Kingsville and Leamington. In addition, floating debris discarded from fishing boats interferes with pleasure craft.

Waste discharges into Pigeon Bay at Leamington have an extensive influence on the adjacent lake waters. In 1967, coliform values as high as 4,000/100 ml were noted within distances of 10 miles from Leamington. Bathing in the adjacent beach areas is, therefore, restricted during certain periods.

Water quality in the midlake section of the western basin is better than the nearshore waters as a result of dilution by the Detroit River mid-channel flow. Turbidity and suspended algae occasionally impair the appearance of the water. The waters of the entire basin are over-enriched, but the nutrient content decreases somewhat toward the northern and eastern parts of the basin (Fig. 3.2.1 to 3.2.3). The average concentrations of total phosphorus ranged from a high of 160 μg/l at the mouth of the Detroit River to 50 μg/l of Pelee Point (Fig. 3.2.1). This would suggest that a large portion of the phosphorus is deposited in the sediments. Orthophosphate concentrations ranged from 15 to 70 μg/l (Fig. 3.2.2). Nitrate-N values of 100 μg/l are about five times higher than those observed in the eastern portion of the lake. Similarly, high nitrite-N (10 μg/l) and ammonia-N values (50 to 80 μg/l) were observed. The rise in ammonia concentration off Little's Point at Colchester is of particular interest. It appears that above average accumulation of organic sediments and their decomposition is reflected in the rise of ammonia concentration. Zones of oxygen super-saturation give an indication of the relatively high algal density and the resulting nuisance and water treatment problems.

Chloride and conductivity distributions (Fig. 3.2.4 to 3.2.5) show the prevalent transport patterns of the dissolved materials entering the lake from the Detroit River.

Central Basin

The immediate effects of waste inputs in the central basin are mainly felt on the United States side in a band a half mile or more in width along shore. Although this band is essentially continuous, it widens somewhat and has higher concentrations of constituents in the vicinity of the larger municipalities which are located at the mouths of tributaries.

Sandusky Bay is contaminated by combined sewer overflows and sewage treatment plant effluents from Sandusky, seepage from septic tank areas, untreated sewage from resort areas around the bay and the discharge of the Sandusky River. The contamination of the bay is not considered serious except in the waters fronting the city of Sandusky where average coliform concentrations have exceeded 6,000 organisms/100 ml. The waters of the bay are characteristically turbid and exhibit over-enrichment in the form of luxuriant *Cladophora* growth. The water supply at Sandusky is treated frequently for excess iron and chlorine-demanding substances especially during periods of northeasterly winds.

From the mouth of Sandusky Bay to the city of Lorain, most of the nearshore waters are of reasonably good quality. Some local problems are caused by silt, turbidity, and algae. Sources of bacterial contamination of nearshore waters exist at Huron and Vermilion.

At Lorain, bacterial concentrations sometimes result in unsatisfactory shoreline water quality. Coliform counts frequently exceed 1,000 organisms/100 ml. This entire area is urbanized and storm water runoff is discharged to the lake. At Lorain toxic metals discharged from industrial sources in the lower Black River are reduced to tolerable concentrations upon mixing with lake water. In addition, synthetic organic wastes from the Black River contribute to taste and odour problems in the municipal water supply. The attached alga *Cladophora* is prevalent in the Lorain to Rocky River area, and the nearshore water is often turbid with silt and suspended algae.

From Rocky River to Willoughby, Ohio, which is the Cleveland metropolitan area, the immediate effects of waste discharges are continuously present. Beaches and nearshore waters are continually fouled with bacteria, debris, and algae as a result of the discharge of grossly contaminated waters from sewage plant effluents, storm and combined sewers, the Rocky and Cuyahoga Rivers, and many small creeks. The bacterial pollution dissipates to 100 coliforms/100 ml at five miles from shore.

Cleveland Harbour, at the mouth of the Cuyahoga, receives highly polluted river water and contains gross amounts of bacteria, organic waste, oils, and other refinery wastes, nutrients, and metals. Oil and grease pollution in the small boat harbours coats the hulls of boats and results in expensive upkeep.

Water quality begins to improve in the less-populated East Lake-Willoughby area and is generally acceptable from this area to Erie, Pennsylvania. Near the large towns at the mouths of rivers, bacterial loadings can be very high as a result of sewage and storm water discharges. The most significant bacterial problems occur at Ashtabula and Conneaut, with occasional problems at Fairport.

There are no major municipal or industrial discharges from the Canadian shore into the central basin of Lake Erie. In these offshore waters, coliform densities were less than 10/100 ml in 1966. An increase to 100/100 ml from Wheatley to Point-aux-Pins in 1967 may be due to local sources. These levels do not limit the use of the waters. However, high oxygen-consuming fish processing wastes discharged to the confined harbour area at Wheatley result in anaerobic conditions within the harbour. The wastes are dispersed within 500 feet beyond the harbour mouth.

Total phosphorus concentrations along the Canadian shore range between 20 to 30 μg/l with the highest concentrations appearing close to shore (Fig. 3.2.1). These slight increases close to shore are characteristic of most other parameters, and are probably due to tributary streams and surface runoff along the shoreline. Orthophosphate-phosphorus concentrations (Fig. 3.2.2) were between 5 and 10 μg/l for the two sampling years, 1966 and 1967. Total phosphorus is approximately one-third and orthophosphate is about one-half the concentration of that found in the Canadian portion of the western basin.

While not shown in the figures, the nitrate-nitrogen concentrations along the Canadian shore are also about one-third those in the western basin. Concentrations between 20 and 40 μg/l close to shore increase to 50 μg/l near tributary outlets.

Ammonia-N concentrations, between 30 and 50 μg/l in 1967, are indicative of active biological decomposition in sediments adjacent to the shore (Fig. 3.2.3). Zones of oxygen saturation generally remained above the 110 percent level both in 1966 and 1967. This is a consequence of high nutrient inputs and resulting biological photosynthetic activity.

Chloride and conductivity distribution patterns (Fig. 3.2.4, 3.2.5) reveal that tributary stream sources contribute moderate amounts of dissolved materials. Traces of phenolic compounds appear occasionally along the shoreline, but are not significant.

Kettle Creek at Port Stanley receives waste waters from the St. Thomas water pollution control plant 15 miles upstream and also untreated domestic wastes from Port Stanley at its mouth. High total phosphorus, nitrate-N and ammonia-N values of 550, 220 and 160 μg/l, respectively, occurring in the harbour, are augmented by nitrogen and phosphates from domestic and fish canning wastes at Port Stanley. The total phosphorus concentrations decrease to 30 μg/l one mile offshore from the harbour. Although high coliform densities were noted in the harbour, median coliform values of 100/100 ml were observed two miles off Port Stanley in 1967.

Eastern Basin

The immediate effects of waste discharges are generally less serious in eastern basin waters of the United States except for certain locations at Erie, Pennsylvania, and the lakefront of the Buffalo metropolitan area.

At Erie combined sewer overflows, storm water, treatment plant effluent, and the large Hammermill paper plant discharges pollute the east end of Erie Harbour, the harbour entrance and occasionally the east end of Presque Isle State Park. Coliform concentrations of up to 500,000 organisms/100 ml in the harbour dissipate quickly in the lake (Fig. 3.2.6). The paper plant discharges also produces a dark brown colour and foam in the affected lake water. This can persist eastwards for several miles along the shore. Otherwise, except for local areas of contamination, the quality of the nearshore water of most of the United States side of the eastern basin is satisfactory.

At Buffalo, the main pollution source is the Buffalo River containing industrial and municipal wastes. These wastes are toxic, oxygen-demanding, highly coloured, and laden with oil. The Buffalo River flows into the lake just above the Niagara River and does not materially affect the lake except for the lakefront.

The Bethlehem Steel Company, south of Buffalo, discharges large quantities of solids and oil. Several other small tributaries containing municipal and industrial wastes discharge to Lake Erie in the southwestern Buffalo metropolitan area. Water quality is therefore, degraded along the shore throughout the metropolitan area.

Nearshore waters at Dunkirk, Silver Creek, and the mouth of Cattaraugus Creek, are intermittently contaminated by municipal and food processing wastes and tributary discharges.

The attached alga *Cladophora* grows luxuriantly on the nearshore bedrock of much of the Pennsylvania and New York shoreline. A recent survey (Federal Water Pollution Control Administration, 1968) showed that *Cladophora* beds covered at least 35 square miles of the south shore of the eastern basin. Enrichment has led to increasing nuisance accumulations on beaches throughout this region. Although nutrient concentrations are relatively low compared to nearshore waters to the west, the substrate, water clarity, water motion and temperature are ideal for *Cladophora* growth.

Untreated sewage discharges at Port Rowan, Ontario contribute to local pollution problems. Total phosphorus and orthophosphate-P levels are as high as 120 and 39 μg/l, respectively, in the vicinity of the outfall but total phosphorus decreases to 65 μg/l within Inner Bay. The Lynn River at Port Dover is a significant contributor of waste waters to eastern Lake Erie. Total phosphorus levels as high as 30 μg/l one mile from the harbour indicate the extent of the influence of this source.

The Grand River (Ontario) is the major Ontario tributary to the eastern basin and significantly influences the quality of water in Lake Erie for a distance of five miles offshore. Total phosphorus concentrations of 1,220 to 2,220 μg/l in the river decrease to 30 μg/l, two miles from the mouth and to 25 μg/l five miles from shore. Orthophosphate-P concentrations between 885 and 1,580 μg/l have been recorded at the mouth. These decrease to concentrations of less than 10 μg/l within three miles from the mouth of the river. Nitrate-N concentrations in the river of 13 to 45 μg/l are above those found in the lake but the effect on the lake is not significant. Nitrite-N concentrations decrease to the 8 μg/l level three miles from shore and to 5 μg/l, five miles from shore. Ammonia-N concentrations of 30 to 50 μg/l found in the river do not differ significantly from concentrations in the lake. A median coliform value of 8,250 has been recorded at the river mouth. Median values were not greater than 34/100 ml two miles from the mouth in 1967 and not greater than 8/100 ml in the same region for 1966.

Algoma Steel Corporation and the International Nickel Company of Canada discharge wastewaters into an area partially enclosed by slag jetties at Port Colborne. The abundant nutrient supply and protected nature of the area encourage the accumulation of algae along the beaches east of the town. The presence of a large rocky shelf at Cassidy Point provides a substrate for the growth of the nuisance alga *Cladophora*. This organism is removed from the substrate and deposited on the beaches by wave action causing an unsightly mess and foul odours. Ultimate control of the problem will require a reduction in the level of nutrients in the area.

The sewage treatment plant at Crystal Beach discharges into Abino Bay. The effects, however, are somewhat accentuated by the protected nature of the bay. Total phosphorus and orthophosphate concentrations are 25 and 13 μg/l, respectively, in the bay. Nitrate-N values are 20 μg/l the same as at the head of the Niagara River. Phenols occur at the 3 μg/l level in Abino Bay which may be due to pleasure craft activities at marinas in the area.

3.2.2 Effects on Water Uses

The pollution factors now interfering seriously with most water uses are over-enrichment and bacterial contamination. Other factors, such as debris, silt, oil, toxic metals, complex organic chemicals, total dissolved solids, and heat are usually limited and local in extent but may exert a more widespread potential threat to water quality and water use.

Public Water Supply

Municipalities on the Canadian shore of Lake Erie withdraw an average of about 23 mgd (Imp) to serve a population of 87,000, while on the United States shore about 600 mgd (U.S.) are withdrawn to serve a population of nearly 2 million. In addition, an unknown but small amount is withdrawn for privately owned cottages.

Lake Erie in general provides a satisfactory source of raw water for domestic supply. The standard treatment usually comprises coagulation, filtration, and chlorination. Microscreening or treatment with activated carbon and algicides is required in the western basin and to some extent in the central and eastern basins of the lake, particularly during the seasons when algae are abundant.

Although treatment techniques are at present available to cope with most circumstances, the cost of providing the necessary facilities and materials does increase with water quality deterioration. Furthermore, processes in normal use cannot cope with sudden detrimental changes in the raw water quality without a sacrifice in the treated water quality or a drastic reduction in the quantity of water produced. The factors of major concern are bacteria, turbidity, ammonia, phosphorus, iron, manganese, and taste and odour producing materials, notably algae. Heavy algal concentrations cause turbidity and obnoxious odours. Algae are also responsible for the clogging of water intakes and for reducing filter life by shortening the period between backwashing. Water supplies in western and eastern Lake Erie are affected to varying degrees by these interferences.

Increased urban and industrial development will require a higher degree of pollution control than is presently available to ensure water of satisfactory quality for domestic water supplies.

Industrial Water Supply

Lake Erie water is utilized by the electric power, steel, chemical, paper, and food industries. The approximate rate of withdrawal in Canada is 30 mgd (Imp) and 4,000 mgd (U.S.) in the United States. Because the use of water for cooling and boiler-feed purposes will be more extensive in the future, the quality characteristics of raw water for these purposes are of great importance. Generally, it is desirable that water supplies for cooling or boiler-feed have a low initial temperature, and be non-corrosive and non-scale forming.

Further, they should be low in suspended solids, dissolved gases, and free of oil and other organic compounds. The demand for both process and cooling water is expected to increase at a greater rate than the demand for domestic water. Although treatment to obtain the desired water quality is entirely a problem of the water user, water quality standards should be maintained to minimize treatment costs.

A substantial amount of process water on the Canadian side is used by the canning industry. A primary consideration for the quality of water used in food canning, and especially in freezing processes, is its bacterial content. It must be free from pathogens and sterile with respect to saprophytic organisms that may cause spoilage. Substances producing tastes, odours, colour, deposits, and toughening of food require strict control.

In conclusion it can be stated that the water presently withdrawn from the lake for industrial uses generally meets quality requirements. However, careful planning of future pollution abatement facilities will be required to meet the industrial demand for good quality water. Any increase in pollution will increase expenditures for water treatment.

Agricultural Water Supply

Irrigation water, withdrawn from the western and central basins of Lake Erie, is used for tobacco growing and market gardening in Ontario. The water quality of the lake does not restrict its use for irrigation.

Recreation, Aesthetics, and Boating

The many beaches and easily accessible nearshore waters make Lake Erie a popular recreational area. Contamination of the nearshore waters reduces the potential for recreation and may discourage other forms of development. Along most of the Canadian shore bacterial contamination is low, but a few shore locations near municipal developments have experienced coliform counts requiring periodic closing of beaches. Along the United States shore, particularly near the larger municipalities, many beaches are bacterially polluted. In contrast to the Canadian shore, only a relatively few beach areas are regarded as continuously safe for swimming. Unless control of pollution sources is obtained, it can be expected that the areas of contamination will progressively expand with increasing urbanization. Growths and accumulations of decaying algae destroy the recreational value of beaches and their associated waters especially in those locations which are protected or have a shallow rocky substrate. Such areas are prevalent around the western and eastern basins.

There have been reports of accumulations of oil and tar on the beaches at Colchester, Point Pelee National Park, and Port Colborne. Most of the oil spills appear to originate from commercial shipping in the vicinity of the Detroit River and near the entrance to the Welland Ship Canal. In one instance in 1959, oil on shore was attributed to leakage from an oil well. Strict enforcement of existing regulations and possibly the implementation of new regulations will be required to control the discharge of oil and other waste materials to the lake.

Propagation of Fish and Wildlife

In the last 25 to 30 years water quality changes have been at least partially responsible for the reduced production of six of the most commercially attractive species in Lake Erie to the point where they have been virtually eliminated. This has caused a shift of production to fish with lower commercial value.

The two main commercial fishing regions of the lake are the western basin and the middle region from east of Point Pelee to west of Port Dover. In these areas sediments have covered previously clean rocky bottoms, and species which ordinarily spawn over gravel or rocky shoals have disappeared from these regions. The more pollution-tolerant species which do not require such rigid spawning and habitat requirements are becoming more dominant. The loss of such spawning areas is believed to be partially responsible for the decline in whitefish, walleye, and blue pike.

The hypolimnion of the central basin has been found to have low oxygen levels in 70 percent of the area in the summer. It is less than the minimum required for healthy fish populations, particularly the cool-water fish stocks that would normally be found there. In addition, occasional periods of low oxygen levels at the bottom of the western basin have caused a reduction in mayfly larvae, the principal food of game fish. This has upset the balance of predator and prey species.

The shore areas that previously had reasonably clean rocky shoals are experiencing increased *Cladophora* growths. The sheltered bays have heavy algal concentrations. As the restrictions encroach on the habitat of sport fish, their numbers will decline. Water fowl become affected by concentrations of pesticides and the increased incidence of oil spills. It is apparent that every effort must be made to improve the water quality of Lake Erie in order to protect its biota and wildlife.

Waste Assimilation

Waste assimilation must not be allowed to interfere with any other use. The extent of municipal and industrial discharges to Lake Erie has been discussed elsewhere. Coupled with the Detroit River input the bulk of the waste loadings are discharged to the western portion of the lake. With increased use of water for municipal and industrial purposes improved waste treatment will be essential to avoid further deterioration in water quality.

Cooling water discharges from thermal generating stations will exert effects on local waters and adequate protection for these waters must be provided in designs for power development.

3.3 LONG TERM EFFECTS

3.3.1 Material Balance

An accounting of the input of materials from municipal, industrial, land drainage and natural sources provides a measure of the origin and fate of the pollutants and a rational basis upon which measures can be taken for the control of water quality. Knowledge of these basic relationships may be used to plan overall water quality programs and specific requirements for the control of pollution.

Rapid increases in the dissolved constituents of Lake Erie have been described in Section 2.3.4 in relation to the levels reported early in this century, for example, the chloride content of Lake Erie is triple the concentration encountered fifty years ago. In Table 3.3.1 the constituents, chlorides, total dissolved solids, total nitrogen and total phosphorus, are compared using the amounts contained in the sum of all inputs to the lake and the quantities carried in the lake outflows. The differences between the total inflows and total outflows are shown as well as the proportion of the inputs from municipal, industrial and land drainage sources.

The sum of the inputs to Lake Erie of chlorides and total dissolved solids are in essential balance with the sum of the outputs from the lake. The retention or alteration of both nitrogen and phosphorus in the lake is shown in the

Table 3.3.1 Materials balance for Lake Erie 1966-67 (thousands of short tons).

	Chlorides	Total dissolved solids	Total nitrogen	Total phosphorus
Lake Huron outflow	1,000	23,700	66	2.2
Total Detroit River input	3,300	29,000	126	17.6
Lake Erie				
Total input	4,500	35,000	194*	30.1
Total output	5,000	36,000	85	4.7
Difference	-	-	109	25.4
Percent retained	-	-	56	84

*Includes 16,000 short tons estimated contribution from atmosphere.

Quantities of phosphorus contributed to
Lake Erie by source (short tons/year)

Source		1967		
Lake Huron		2,240		
	U.S.		Canada	Total
Detroit River				
Municipal	10,750		760	11,510
Industrial	350		630	980
Land drainage	1,490		1,380	2,870
Sub-Total		17,600		

Table 3.3.1 (cont'd)

Source	1967		
	U.S.	Canada	Total
Point Sources			
Municipal	2,710	30	2,740
Industrial	Nil	20	20
Sub-Total			2,760
Other Municipal Tributaries			
Municipal	4,360	480	4,840
Industrial	560	470	1,030
Land drainage	3,320	550	3,870
Sub-Total			9,740
Total-Municipal and Industrial			21,120
Total-Other Sources			8,980
TOTAL			30,100

difference between the inputs and outputs. The phosphorus retained in the lake is 84 percent while more than 50 percent of the nitrogen supplied is retained. It is noted that about 70 percent of the total phosphorus input to Lake Erie is contributed by municipal and industrial sources, whereas only 30 to 40 percent of the nitrogen originates from these sources.

3.3.2 Transboundary Movement of Pollutants

One of the three main questions asked in the International Joint Commission Reference is whether the waters of Lake Erie are being polluted on either side of the international boundary to an extent which is causing or is likely to cause injury to health or property on the other side of the boundary. Technical information included in earlier sections of this report, especially on circulation of lake waters (Section 2.1.2), on water chemistry (Section 2.3) and on sources of material inputs (Section 3.1) are considered in this section for an assessment of transboundary movements of pollutants.

The Detroit River, besides being the prime source of water supply to Lake Erie, is unique in that the mid-channel flow approaches the quality of Lake Huron water, while along the banks, the water quality is seriously degraded by wastes entering from the metropolitan area of Detroit. This condition is maintained far into the western basin of Lake Erie, the mid-channel flow tending to keep both the Canadian and United States wastes along their respective shores.

The waters along the Michigan shore are joined by the flows from the Raisin, Huron and Maumee Rivers. This produces a large area, west and south of the Detroit River mouth, which is relatively rich in nutrients, chlorides, and other constituents. Concentrations decrease rapidly from this area eastward due to dilution by the Detroit River, however some of this enriched water remains relatively undiluted as it flows east along the Ohio shore. On the west side of the islands the dominant flow is northward across the western basin and the international boundary. In the northern half of the basin the main flow from the Detroit River is predominantly eastward. This flow and the northward flow join to enter Pelee Passage.

The inflowing water to the central basin is fairly homogeneous with its constituent load mainly originating from United States sources. The bulk of the flow is southward from Pelee Passage across the boundary. In the central basin the distribution of input materials is quite different from that in the western basin. South shore inputs, which are very great compared with north shore inputs, tend to move eastward in a band along shore. They gradually disperse into the lake as they are moved eastwards. However, under certain seasonal conditions, they may be moved directly offshore.

After inputs have reached far enough offshore to be dispersed in midlake waters, further travel can be extensive throughout the basin. Bottom waters and their characteristic constituents have a predominant movement northwestward from the United States side to the Canadian side of the lake. Surface water movements are predominantly the reverse - from the Canadian to the United States side.

In the eastern basin the circulation patterns are somewhat similar to those of the central basin. Surface water moves predominantly across the lake from Canada to the United States. Bottom water motion is less well identified but the indications are that it moves from the United States to Canada. In the eastern basin the nearshore flow is less distinct than in the central basin and inputs may be more quickly dispersed into the lake.

A simple indirect manifestation of transboundary movement of constituents lies in the distribution of conservative dissolved substances. For example, let it be assumed that the Lake Huron outflow be assigned equally to United States and Canadian sources, and that no transboundary movement of water occurs below the Lake Huron outlet. Then the concentration of chloride in the Canadian waters of Lake Erie, based on waste discharges to the Canadian waters, should be approximately 10 mg/l. Likewise, the concentration of chloride in the United States waters of Lake Erie, based on waste discharges to United States waters, should be more than 30 mg/l. The chloride concentrations, especially in the central and eastern basins are remarkably uniform across the lake, averaging about 25 mg/l, indicative of complete mixing of conservative materials.

Although transboundary movement of water can be demonstrated using stable dissolved constituents, it is another matter to show damage to one side as a result of inputs of these materials from the other side of the lake. Conservative materials in Lake Erie as a whole are not of major concern at the present time. Substances which are recognized to be damaging are generally non-conservative nutrients, oxygen-consuming substances and bacterial pollution. Bacteria can be discounted because of their limited viability. An exception is the Detroit River mouth where high bacteria counts can occasionally be traced to a source across the boundary. However even here the travel into other waters is not far and one shore is not measurably affected by discharges from the other. Similar statements can be made regarding discharges of oxygen-consuming substances. These materials are generally of concern only in the vicinity of the discharge since extended transport results in oxygen demand satisfaction.

North shore waters do not generally appear as productive as south shore waters in relation to the growth of algae. The south shore productivity results from the immediate response of algae to the large nutrient inputs along that shore. The algal response on one side of the lake if sources on the opposite side were stopped is not known, but it appears that the United States side would be little affected by a cessation of Canadian inputs. With reduction of all inputs, improvements are expected to result in the lake.

Midlake waters are now less productive than waters near shore, although midlake productivity shows evidence of over-enrichment. For example, the loss of dissolved oxygen in central basin bottom waters on both sides of the boundary is a consequence of high algal production. Blooms of blue-green algae in late summer in the northwestern part of the central basin appear to result from upwelling of nutrient-laden bottom waters.

In summary, it can be stated that all of Lake Erie is being adversely affected by pollution, primarily in the form of nutrients. It is a total lake problem, meaning that inputs from both sides are eventually mixed, causing damage to water uses on both sides. Although the degree of damage varies from mild to serious in various parts of the lake, the condition in the lake generally may be regarded as having been caused by nutrient inputs from both the United States and Canada. Each country's share of the cause can be viewed as being roughly proportional to its share of the nutrient inputs.

3.3.3 State of Eutrophication

The state of eutrophication of Lake Erie can only be evaluated by comparison with other lakes of the world. Diverse criteria have been proposed for the classification of lakes as oligotrophic, mesotrophic and eutrophic by phytoplankton abundance, phytoplankton production, species associations of planktonic and benthic communities, nutrient concentrations, nutrient loads, sediment types and fish production. Although none of these provides a reliable overall characterization, they do collectively yield a framework within which it is possible to classify lakes broadly according to their trophic states.

Table 3.3.2 gives an overall evaluation of the current trophic states of the three basins of Lake Erie based on information from diverse sources, together with comparable information for Lake Ontario. As a relatively shallow body of water (mean depth 18 metres as compared to 84 metres for Lake Ontario) Lake Erie is morphometrically predisposed toward eutrophy. This is particularly the case for the western basin (mean depth 6.7 metres) where the waters are isothermal and circulate freely to the bottom during ice-free seasons. Oxygen depletion occurs in the bottom waters of the deeper central and eastern basins during periods of restricted vertical circulation due to microbial oxygen consumption within a small hypolimnetic volume.

The three interconnected basins of Lake Erie differ in their trophic states. The western basin is clearly eutrophic. The central basin is mesotrophic with some eutrophic tendencies, and the eastern basin is mesotrophic with an occasional representation of some oligotrophic species (Table 3.3.2). Data on nutrient concentrations summarized in Section 2.3 lead to the same conclusions from the observations of nutrient levels at 60 μg total-P/l and 740 μg total-N/l in the western basin and 20 μg total-P/l and 470 μg total-N/l in both the central and eastern basins in 1967 (Federal Water Pollution Control Administration, 1968). It must be recognized, however, that most of the nutrient data pertain to late spring, summer and autumn when nutrients are depleted by algal growth.

In nearshore environments, particularly in the vicinity of population and industrial centres and at the mouths of rivers draining agricultural regions, there is clearly a greater degree of eutrophication than that of the main body of Lake Erie (Sections 2.3, 2.4 and 3.2). Nutrient and algal concentrations are very high, with oligochaetes and *Chironomus s.s.* dominating the benthic fauna to a greater extent than is the case in offshore areas. Pronounced eutrophication at nearshore sites in Lake Erie occurs at the mouths of the Detroit, Grand, Maumee and Raisin Rivers, in Sandusky Bay, and around the Cleveland metropolitan area (Sections 2.4 and 3.1). *Cladophora* constitutes a serious problem on beaches around the eastern basin from Erie, Pennsylvania to Port Dover, Ontario on the Canadian shore, and in the island area of the western basin of Lake Erie.

Vollenweider (1968) has proposed criteria to evaluate the state of eutrophication of lakes based on a knowledge of the loadings of total-P and total-N delivered from both natural and cultural sources. In order to permit a comparison of lakes with different areas and volumes, the annual loadings are

Table 3.3.2 Best overall estimates of current trophic states in the open waters of the three basins of Lake Erie and in the open waters of Lake Ontario. It must be recognized that the range from oligotrophy (O), mesotrophy (M), and eutrophy (E) is continuous.

Category	Lake Erie western basin	Lake Erie central basin	Lake Erie eastern basin	Lake Ontario
Physico-chemical:				
Morphometry	E	M-E	O-M	O
Transparency	E	M	M	M
Nutrient concentrations	E	M	M	M
Nutrient loading		E*		M
O_2 in hypolimnion	**	M-E	O	O
Biological:				
Phytoplankton	E	M	M	O-M
Zooplankton	E	M	M	O-M
Bottom fauna	E	M-E	O-M	O-M
Fish production		E*		O
Overall assessment:	E	M-E	O-M	O-M

*For the lake as a whole
**The western basin of Lake Erie is normally unstratified in summer.

expressed as grams of total-P or total-N per square metre of lake surface. Predicted effects are then evaluated as a function of mean depth of the lakes in question, thus bringing all comparisons to a standard volume of lake water.

Table 3.3.3 lists the admissible and dangerous loading limits proposed by Vollenweider (1968). From data presented in Section 3.1 of this Volume, the annual loadings of total-P and total-N for Lake Erie are 30,000 and 194,000 short tons per year, respectively. Converted to a unit area of lake surface these correspond to 1.1 g total-P/m^2.yr and 6.8 g total-N/m^2.yr. The admissible and dangerous loading limits for a lake of 20 metres mean depth (*versus* 18 metres mean depth for Lake Erie) from Fig. 3.3.1 are 0.15 and 0.30 g/m^2.yr, respectively, for total-P. The corresponding limits for total-N are 2.2 and 4.5 g/m^2.yr, respectively (Fig. 3.3.2). The actual lake loadings for both elements are thus well above the "dangerous" limits proposed by Vollenweider. The loading for total-P in the western basin of Lake Erie (21,000 short tons per year) is 40 times the "dangerous" limit when expressed on a unit area basis for the western basin.

Nutrient loading data for Lake Erie as a whole and for the western basin are plotted in Fig. 3.3.1 for phosphorus and Fig. 3.3.2 for nitrogen. A weight ratio of 15N:1P (the average for algal protoplasm) has been used to interrelate the loadings of the two elements in terms of potential for algal growth. It must be stressed that these graphic relationships are primarily based upon empirical observations rather than theoretical relationships. For those reasons they provide a solid framework for comparison, largely free of assumptions. They do not, however, fully take into account the varying rates of replacement of water in the lakes shown.

It can be inferred from early data on fish populations, the low mean depth of the lake, and the rich soil and sedimentary rock drainage area, that Lake Erie was a biologically productive lake prior to major human settlement. The complete elimination of nutrient loading from municipal and industrial sources will thus never create oligotrophic conditions comparable to those in the upper Great Lakes. At present the combined nutrient loading from municipal and industrial sources accounts for 30 to 40 percent of the total-nitrogen and 70 percent of the total-phosphorus from all sources. At best there would be a return to conditions existing in the early part of the 20th Century. If, on the other hand, control by nutrient removal is not practiced, and the projected loadings for 1986 are realized, there is every reason to expect further pronounced biological changes that will result in a deterioration of overall water quality.

Table 3.3.3 Estimates of admissible and dangerous loading limits for total-N and biologically active total-P as a function of mean lake depth (After Vollenweider, 1968)*.

Mean depth (metres)	Admissible loading ($g/m^2.yr.$) total-N	total-P	Dangerous loading ($g/m^2.yr.$) total-N	total-P
5	1.0	0.07	2.0	0.13
10	1.5	0.1	3.0	0.2
50	4.0	0.25	8.0	0.5
100	6.0	0.4	12.0	0.8
150	7.5	0.5	15.0	1.0
200	9.0	0.6	18.0	1.2

*Vollenweider (1968) gives these values only as preliminary and tentative estimates.

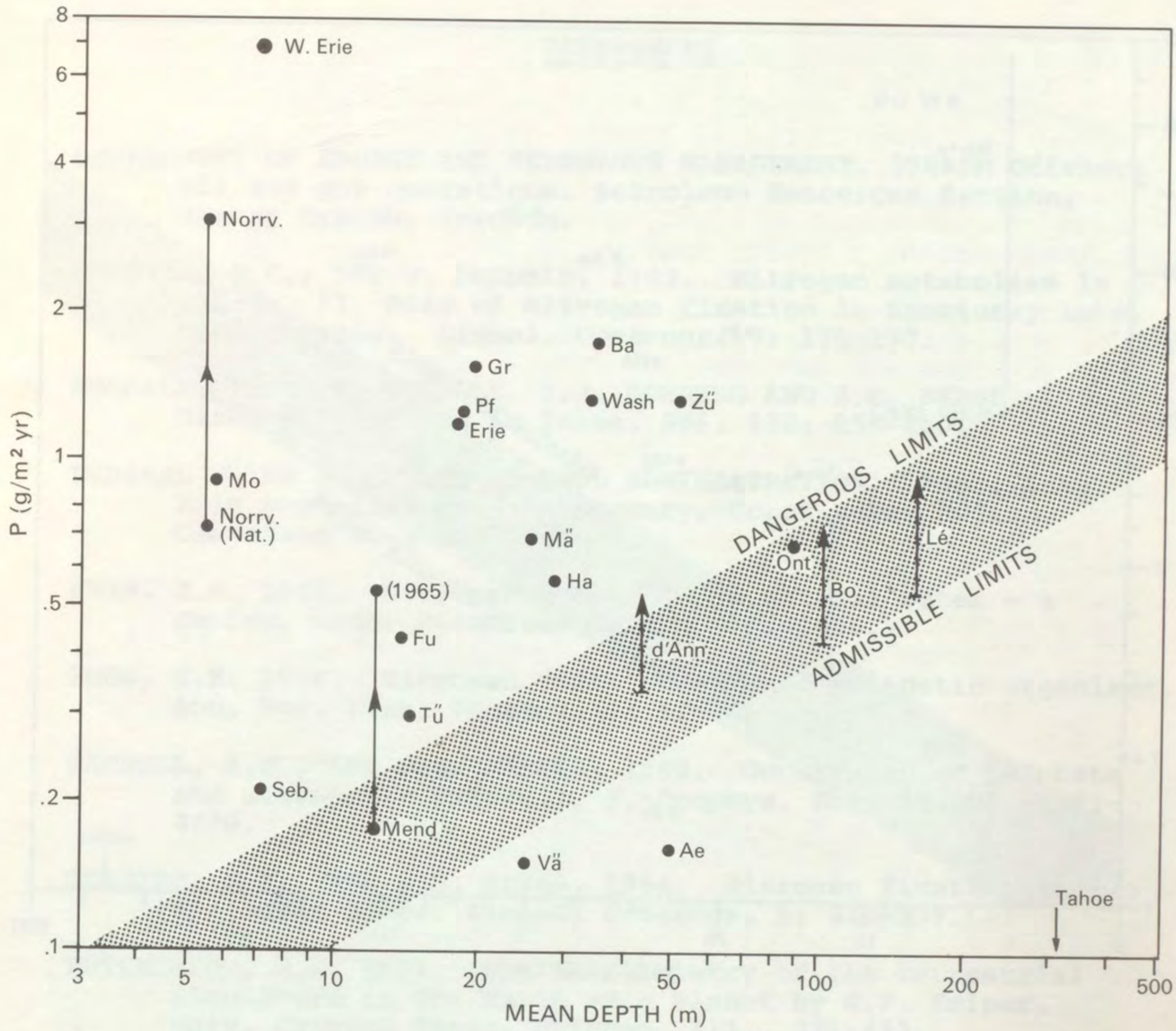

Fig. 3.3.1 Phosphorus loading *versus* mean depth for various lakes.

Abbreviations: Ae (Aegerisee), Ba (Baldeggersee), Bo (Bodensee, Obersee), d'Ann (Annecy), Fu (Furesø), Gr (Greifensee), Ha (Hallwilersee), Lé (Léman), Mä (Mälaren), Mend (Mendota), Mo (Monona), Norrv (Norrviken), Ont (Ontario), Pf (Pfäffikersee), Seb (Sebasticook), Tü (Türlersee), W. Erie (western basin, Lake Erie), Wash (Washington), Vä (Vänern), Zü (Zürichsee). The value for Bodensee is twice the value for orthophosphate-P (After Vollenweider, 1968).

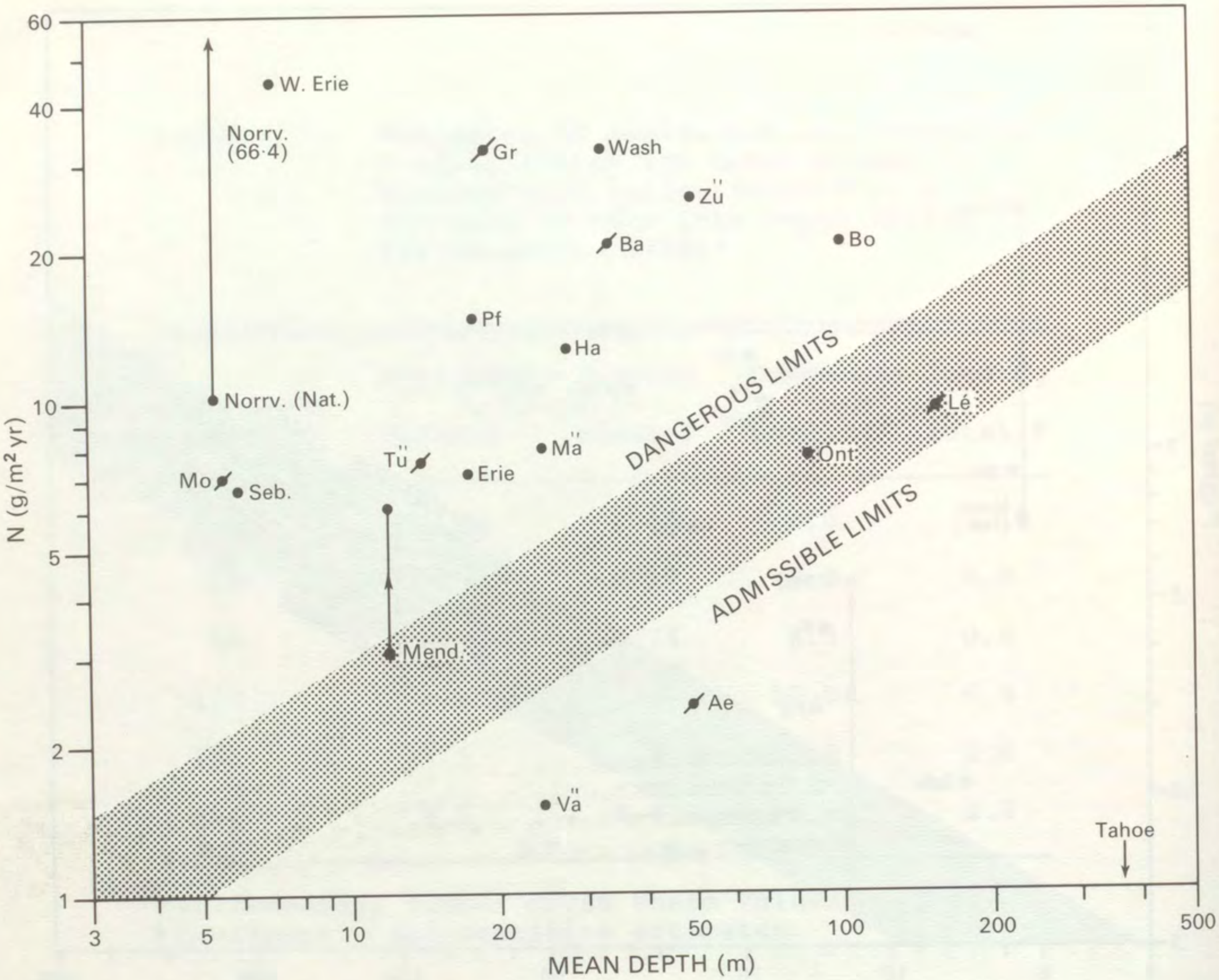

Fig. 3. 3. 2 Nitrogen loading *versus* mean depth for various lakes.

Abbreviations: Ae (Aegerisee), Ba (Baldeggersee), Bo (Bodensee, Obersee), Gr (Greifensee), Ha (Hallwilersee), Lé (Léman), Mä (Mälaren), Mend (Mendota), Mo (Monona), Norrv (Norrviken), Ont (Ontario), Pf (Pfäffikersee), Seb (Sebasticook), Tü (Türlersee), W. Erie (western basin, Lake Erie), Wash (Washington), Vä (Vänern), Zü (Zürichsee). The dots with slanted lines refer only to inorganic-N (After Vollenweider, 1968).

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4. DEVELOPING PROBLEMS

Protection of the uses of water such as public, agricultural and industrial water supplies, fish and wildlife conservation, recreation and aesthetic enjoyment requires the successful control of all pollution sources. Where high quality water exists the necessary steps should be taken to prevent a deterioration of the existing quality and thus preserve the water for future use.

Water quality investigations have shown that existing measures to control water pollution have not advanced sufficiently to satisfy the needs of all water uses. Unsatisfactory conditions occur in harbours and in the local waters of Lake Erie where offensive accumulation of debris and growth of aquatic plants are often found near waste water discharges. In view of the large population and industrial growth anticipated within the Lake Erie drainage basin over the next twenty years, restrictions on development will become necessary unless adequate provision can be made to restore and maintain water quality. The main problem that has emerged in the study of Lake Erie is the need to control sources of nutrient materials emanating from waste discharges and land drainage.

4.1 MUNICIPAL AND INDUSTRIAL WASTES

Estimates of the total phosphorus expected from the urban population and industrial development projected by 1986 for the Lake Erie basin are presented in Table 4.1.1. The contributions from the forecasted populations are based on an expected phosphorus wastage ratio of 3.5 pounds per capita per year of which 2.5 pounds per person will originate from detergent phosphorus. At present it is estimated that 50 to 70 percent of the total input of phosphorus from all municipal and industrial wastes in the lower Great Lakes basin comes from detergents. The increases in phosphorus sources will account for a doubling of the quantities now supplied to the lake to a level of 45,000 tons per year by 1986.

Reference to Fig. 5.1.1 and Table 5.1.1 illustrates the significance of this total phosphorus loading on Lake Erie. When expressed as an annual loading rate, per unit of surface area, the 1986 input of phosphorus indicates that a considerable advance in the degree of eutrophication in the lake can be expected.

In the past few years the economic growth rate in the Lake Erie basin has been of the order of four percent

Table 4.1.1 Annual input of total phosphorus (short tons/year) projected to 1986.

Source	Projected for 1986 without control measures		
Lake Huron	2,600		
	U.S.	Canada	Total
Detroit River			
Municipal	15,000	1,050	16,050
Industrial	1,000	1,580	2,580
Land drainage	1,600	1,500	3,100
Sub-Total	24,330		
Point Sources			
Municipal	4,000	50	4,050
Industrial	-	50	50
Sub-Total	4,100		
Other Major Tributaries			
Municipal	8,000	1,050	9,050
Industrial	1,000	1,180	2.180
Land drainage	4,000	950	4,950
Sub-Total	16,180		
Total-Municipal & Industrial	33,960*		
Total-Other Sources	10,650		
TOTAL	44,610		

*It is estimated that 70 percent of this will be from detergents.

annually. If this rate of growth continues industrial production and industrial waste loadings should almost double by 1986.

Several important factors will affect future output of industrial wastes such as changes in manufacturing processes, advances in treatment methods, improved efficiency of materials handling at existing manufacturing plants, and improved treatment facilities.

The present variety of waste materials ranging from acids and alkalis, phenolic and organic substances, oils, metals, phosphorus and nitrogen containing wastes will expand as new types of manufacturing processes are employed in the future.

Organic contaminants include the persistent or biochemically resistant compounds which increasingly occur in municipal and industrial wastes from new product formulations, insecticides, herbicides, and other agricultural chemicals. In view of their persistent and toxic nature, even in low concentrations, they pose a growing threat to water quality and the aquatic environment.

Radioactive wastes from nuclear reactors, waste processing plants, industrial, medical and research uses are either discharged to the lakes directly or through municipal sewers. While the amount of radioactivity that can be discharged to surface waters by nuclear operations is controlled by government regulations, the release of these substances to the environment is increasing with the development of nuclear power generation facilities. It should be noted that all values of radionuclides are well below maximum permissible concentrations recommended by the International Commission for Radiological Protection (ICRP) and are within the allowable limits of the public drinking water standards in the United States and Canada.

Finally, water must be considered as a possible vector in the transmission of viral diseases. Viruses of human, animal and plant origin could reach potable water supplies by means of urban and rural runoff or via direct discharge. The latter could occur by allowing animals direct access to the body of water, by discharge from pleasure or commercial watercraft, or from municipal and domestic sewage treatment plants. The viruses which have been most intensively studied in connection with water supplies are those of the enteric group (Poliomyelitis, Echo, Coxsackie viruses, etc.), which are pathogenic to humans. However, some other viruses of animal origin may also be capable of causing infection in man, but the significance of these and plant viruses in water is largely unknown.

There is a large volume of evidence to indicate that many of the treatments afforded sewage are not adequate with respect to viruses; viable viruses have been isolated in effluents from sewage plants employing tertiary treatment, and they are not inactivated in lagoons or septic tanks. As has been noted elsewhere, some sewage enters the lakes untreated and would certainly contain viruses.

The number of viable viruses present at any given point would be dependent on several factors such as proximity to large urban areas, bathing beaches, agricultural areas and so on. Winds and currents would tend to disperse and dilute any concentrated discharge and play a part in reducing viruses to a non-infective level. Where, however, there is the possibility of survival of even low numbers of viruses, such as in the nearshore waters where pollution is greatest, there should be cause for concern, since it is these very regions that are used for recreation and water supplies.

4.2 LAND DRAINAGE

Nutrients and other materials in land drainage reflect local and regional land use practices and are contributed in varying amounts by the tributaries to Lake Erie (Section 3.1.3). Replacement of forest cover by farm crops and urban development has resulted in increased soil erosion and greater fluctuations in natural streamflow. Favourable conditions have been created for the leaching and transport of soluble and suspended materials from the land surface. Techniques for the application of pesticides, methods of livestock waste disposal and practices of soil fertilization and land tilling will continue to have a direct bearing on stream quality. By 1986 the amount of phosphorus contributed from land drainage is expected to increase by about 20 percent.

Although the quantities of pesticides and herbicides applied each year do not vary appreciably, there is a trend towards the use of more potent chemicals. This has been the case since the introduction in 1945 of hydrocarbon compounds and since 1950 when a range of organic pesticides was brought onto the market. Since most of the compounds presently in use resist biological breakdown, their use has resulted in increasing residual concentrations in surface waters and aquatic fauna. Water quality problems can be reduced by more discriminate application of pesticides and the use of chemicals which are readily degradable. Another possible approach is the substitution of biological control of pests instead of chemical control.

The intensive production of livestock in feed lots will require improved provision for the handling and disposal of animal wastes to avoid pollution of water. The practice of fertilizing farm lands in the winter with animal wastes requires attention since it results in large pollutional runoff loads in the spring. Streambank erosion, resulting from overgrazing along river banks and re-channelling is another contributing factor.

In Ontario, animal waste disposal in the drainage basin amounted to an estimated 10,000 tons per year of phosphorus and 47,000 tons per year of nitrogen. The wastes are attributed principally to livestock including beef and dairy cattle, laying hens, pullets, broiler chickens, and market hogs. It is estimated that 15,000 tons of phosphorus and 67,000 tons of nitrogen are produced by the cattle, chicken and hog population in the United States section of the basin (Federal Water Pollution Control Administration, 1968).

A total of 12,000 tons of phosphorus and 20,000 tons of nitrogen were applied as chemical fertilizers in the Erie basin of the province of Ontario in 1967. This represents an increase in application of 90 and 200 percent for phosphorus and nitrogen, respectively, from 1960 to 1967. In 1964, 59,020 tons of phosphorus and 120,000 tons of nitrogen were applied on the United States side (U.S. Department of Agriculture, 1966).

4.3 THERMAL INPUTS

The temperature of Lake Erie, because of the lake's shallow depth and its southern location, is naturally higher than that of the other Great Lakes. Summer temperatures of surface waters commonly reach 75°F and in protected areas often exceed 80°F. The temperature alone is conducive to Lake Erie's great productivity.

The major producers of waste heat to the lake are the power generation facilities in the United States portion of the basin. Eleven plants, one which is nuclear-fueled, now discharge waste heat to the lake. Six plants discharge to the Detroit River (Fig. 4.3.1). The present capacity of these 17 plants is about 8,000 Mw. Production is expected to increase to at least 15,000 Mw by 1986 in the United States portion. A coal-fired generating station is under construction near Nanticoke, Ontario with a planned production capability of 2,000 megawatts by 1971. Two nuclear-fueled plants are being considered, one along the Ohio shore and one on the Michigan shore of the western basin. It is anticipated, however, that the bulk of power production will continue to depend on fossil fuels beyond 1986.

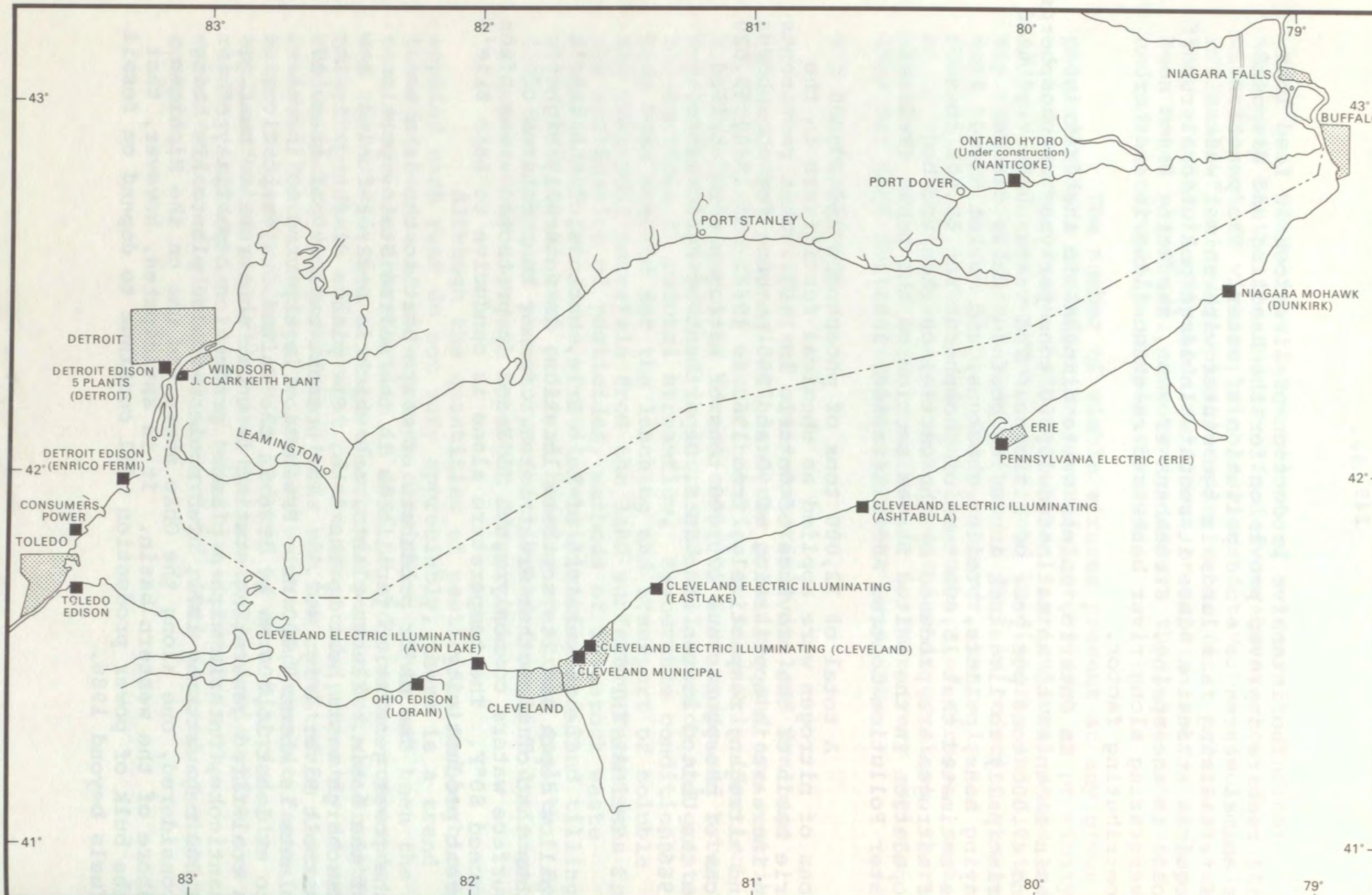

Fig. 4.3.1 Locations of major thermal electric power facilities in the Lake Erie basin, 1968.

The second largest producers of waste heat in the Erie basin, are the metal industries, primarily iron and steel. Their heat production is insignificant in comparision with that of the power industry but it does cause local problems.

Localized effects of thermal pollution, particularly near the shoreline, include stimulation of algal growth, depletion of dissolved oxygen, and possible alteration of the entire local ecology. The effect of waste heat input on the lake as a whole is not considered to be significant. The total waste heat input to Lake Erie is of the order of 15×10^9 BTU per hour or only about 0.13 percent of the natural input, 11.2 $\times 10^{12}$ BTU per hour for the period of warming.

The effect of thermal pollution on the quality of water and the aquatic environment has been the subject of extensive studies both in the United States and Canada. The studies have not been carried far enough to establish prediction models for the purpose of engineering design as yet. Additional research and observation will be necessary to predict and assess the effects of thermal discharges to the lakes in order that improved guidelines for future installations can be developed and applied. Proper engineering of intake and outfall structures must insure that local warming effects will be kept to a minimum.

4.4 OIL AND MATERIAL SPILLS

The effects of accidental spills and releases of oil may interfere seriously with most water uses. Oil may be lost during manufacturing operations, production, storage and transferring activities involving terminal and dockside facilities, tank farms, freighters, pipelines, tank cars and trucks.

Apart from major oil spills, severe cases of local pollution have occurred as the result of mishaps in transferring petroleum products between ship and shore, discharging ballast from vessels, cleaning oil tanks and from the negligent discharge of oily bilge wastes. These incidences occur at the rate of several a month during the shipping season on the Great Lakes. A number of sunken ships in Lake Erie and Lake Ontario also pose a threat from oil pollution. Other sources of oil pollution are waste oil from gasoline filling stations, accidental spillage during industrial transfer and storage, leaks from pipelines and related systems.

Continuous discharges and seepages of oil occur from municipalities and industries into Lake Erie and its tributaries. It is estimated that the input of oil and grease to the Detroit and St. Clair Rivers is in excess of about 1,100 barrels per day. Of this total approximately 80 barrels of ether soluble materials (greases and oils) are being discharged from Ontario municipal and industrial sources. While these figures indicate the amount of oil and grease lost daily a single recorded oil loss in excess of 3,000 barrels occurred in less than a six hour period from one of the petrochemical industries on the St. Clair River.

Oils are also released in the disposal of dredging spoils as revealed by the studies of dredging operations in Cleveland Harbour for 1966 and 1967. Over 100,000 barrels (17,600 short tons) of oil and grease were disposed of in the lake during this project (Table 3.1.9).

4.5 LAKE LEVELS REGULATION

Proposals to regulate the levels of the Great Lakes have been considered in the past, particularly during periods of high water stages. The Corps of Engineers was directed, in 1952, to determine the feasibility of regulation and its affects on navigation, power development, and shore property.

A reference to the International Joint Commission in 1964 requested the Commission to study lake level regulation and its practicability in improving:

(a) domestic water supply and sanitation

(b) navigation

(c) water for power and industry

(d) flood control

(e) agriculture

(f) fish and wildlife

(g) recreation

(h) other beneficial public purposes

If regulation is considered practicable the Commission is to indicate how various interests will benefit or be adversely affected. A lake levels advisory board was appointed by the International Joint Commission and the board has been meeting regularly to prepare a report for the International Joint Commission in regard to the above reference.

The objective of regulation is to reduce the extremes of seasonal and long-term lake stages. High stages should, therefore, be lowered and low stages raised. A constant or fixed level is not feasible nor is the reduction of daily extremes caused by meteorological disturbances.

Raising or lowering the level of Lake Erie will not greatly affect the overall water quality of the lake. The average level of Lake Erie would be reduced less than 0.12 metres, representing a reduction of average volume by 0.7 percent, an insignificant factor in relation to constituent concentration. Lake-wide concentration extremes (± 4 percent of the average) which now occur in response to changes in volume, would be brought to a narrow range (± 2.5 percent of the average). Reduced levels will likely cause an increase in the growth of attached algae.

Regulated inflows and outflows, which would control levels, potentially present a much more significant pollution aspect. Further, the inflow would be more important than the outflow, because of the physical characteristics of the western basin and because the largest pollution source to Lake Erie discharges directly to this inflow.

The average monthly outflow from Lake Huron is 187,000 cfs. The largest recorded has been 229,000 cfs and the minimum, 105,000 cfs. The Corps of Engineers plan calls for a maximum of 258,000 cfs and a minimum of 76,000. Each of these is 29,000 cfs greater than the present recorded extremes.

Assuming, as an example, that the average chloride concentration in the Detroit River discharge is 18 mg/l at 187,000 cfs, the concentration at 76,000 cfs will be 34 mg/l, and at 258,000 cfs, 15 mg/l. These concentrations are, respectively, 20 percent above and 6 percent below the extremes which might be expected without regulation. These calculations assume in addition that the Lake Huron discharge is constant at 7 mg/l regardless of flow and that other inputs to the St. Clair-Detroit River area are constant at 11.1 million pounds per day.

The retention or "fill-up" time of the western basin of Lake Erie averages about 50 days for the average flow of the Detroit River. Correspondingly the average chloride concentration is 18 mg/l, the same as that of the Detroit inflow. It is theoretically possible for a Detroit River inflow of 258,000 cfs to reduce the concentration to 15 mg/l in 30 days, while an inflow of 76,000 cfs could raise the concentration to 34 mg/l in 125 days. The latter is not likely to occur. An average concentration of 25 mg/l is likely to occur annually in late winter with low flows, some 20 percent above the maximum average expected without regulation.

Chloride has been used to demonstrate what can happen with lake level regulation in the western basin of Lake Erie. More importantly other constituents, absent or present in only minute quantities in the Lake Huron outflow but discharged in large quantities in the Detroit area, will show even greater variations in the western basin with controlled flows. Toxic material concentrations, oxygen-demanding substances, and nutrients could show great damage to western basin water quality if their concentrations are increased above an already serious level.

The timing of regulation operations is important, the highest input concentrations would be in the winter, January and February. Highest western basin concentrations would be at the beginning of spring, a critical time for lake biota. Regulated inflows would be significantly lower than past averages and, therefore, concentrations could be expected to be somewhat higher than in the past. Offsetting this to some degree would be higher flows for dilution in summer but the effects would not compensate the damages which occur in spring, especially to fish spawning and other spring phenomena. In the central and eastern basins the lake regulation should not show significant effects on pollution because the long-term averages become more important.

At the east end of Lake Erie regulatory works in the Niagara River would control outflow. The outflow would be maintained as high as possible, consistent with regulation. This flow would probably be sufficient to prevent a build-up of waste constituents in Lake Erie from the Buffalo area. The effect on the Niagara River could be very significant, especially if pollutants such as oil were allowed to build up above the gates and then were released, later as large slugs.

In summary, lake regulation would lower water quality in the Detroit River and in the western basin during winter and spring. Flows would still remain insufficient to compensate for the damages to water quality in the summer, but benefits would accrue from a reduction of shore erosion problems.

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concentration to 34 mg/l in 122 days. The [illegible] to [illegible]. An average concentration of 25 mg/l [illegible] expected, especially in late winter with low flows, [illegible] percent above the Detroit average expected without [illegible].

[illegible] other constituents, [illegible] discharged in large quantities, [illegible] show similar variations in the western basin with controlled [illegible] constituents [illegible] western basin water quality if their concentrations are increased above an already critical level.

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5. CONCLUSIONS AND SUMMARY

5.1 RATIONALE FOR PHOSPHORUS REMOVAL

The most serious water pollution problem in the lower Great Lakes, having long term international significance, is the increasing eutrophication of the lakes. This deterioration of water quality, due to the luxuriant growth of algae and other plants and its repercussions on the overall biota of the lakes, is clearly the result of the increasing input of fertilizing nutrients from municipal sources, industrial wastes and land drainage. Although many of the most obvious effects appear localized, each lake is being adversely affected across the international boundary by nutrient enrichment from essentially all sources in both countries. Unless action is taken by Canada and the United States to reduce the nutrient input and fertilization of the lakes, there will be an ever increasing deterioration of water quality.

Complete diversion of municipal and industrial wastes would no doubt be the surest method of eliminating the majority of all nutrients from human-derived sources. This method has been successfully carried out on a number of small lakes through the construction of a complete canalized system which carries all wastes away from the lake. Unfortunately, complete diversion from Lakes Erie and Ontario is not economically possible due to the volume of wastes involved and the distances to the sea. With the present state of knowledge and technology, the only feasible approach to the problem in the lower Great Lakes is the removal of specific nutrients from wastes.

Phosphorus and nitrogen are recognized as the most important nutrients responsible for eutrophication. Trace elements and organic growth substances also play a part, although, their roles are inadequately understood as yet. The experience in many lakes indicates that phosphorus is most often the controlling material.

The reasons for proposing phosphorus removal from wastes to combat eutrophication are:

1. that in most natural waters the growth of algae is controlled more by the supply of phosphorus compounds than by the supply of nitrogen compounds. Other nutrients are generally of less importance. There is every reason to believe that this is also the case for Lakes Erie and Ontario.

2. that the loading of phosphorus to the lakes can be controlled more effectively than that of nitrogen (70 percent of the total phosphorus contributed to Lake Erie is attributable to municipal and industrial sources, *versus* 30-40 percent for nitrogen; comparable figures for Lake Ontario are 57 percent for phosphorus and 30 percent for nitrogen).

3. that efficient and relatively inexpensive methods are available for 80-95 percent removal of phosphorus during sewage treatment, whereas comparable elimination of nitrogen compounds is not yet feasible.

4. that nitrogen is contributed more from uncontrollable sources than phosphorus because:

(a) phosphorus has a higher natural retention in soils than nitrogen.

(b) phosphorus is subject to further losses by natural biological sedimentation processes.

(c) the release of phosphorus from bottom sediments to water is less both in magnitude and in percentage than is the case for nitrogen.

(d) appreciable quantities of readily assimilable nitrogen compounds (nitrates and ammonia) are delivered directly to the lakes in precipitation. The comparable quantities of phosphorus are so low that they have yet to be accurately measured.

(e) during times of nitrate deficiency in surface waters some blue-green algae can utilize N_2 derived from the atmosphere as a source of nitrogen. An equivalent phenomenon does not exist for phosphorus uptake.

The most direct and obvious evidence of the importance of phosphorus in the enrichment of the lower Great Lakes by man's wastes comes from recent culture experiments which are summarized in Volume 1 (Vallentyne, 1969).

Consideration of phosphorus removal as a remedial measure for controlling eutrophication has two fundamental requirements. First, reliable estimates of the total input (loading) of phosphorus and the input from the various sources are required in order to estimate the extent of reduction that can be achieved (at the present time, it is assumed that only municipal and industrial wastes are amenable to direct control). Estimates of nutrient input from all sources have been a substantial part of the work in the preparation of this report. Tables 5.1.1, for Lake Erie, and 5.1.2, for Lake Ontario, give the inputs of total phosphorus from the various sources for the present time (1967) and the projected inputs for 1986 if no remedial measures are undertaken. These projections allow for anticipated population and industrial growth in the Great Lakes region. The tables also give the projected total loading in 1986, if by then all phosphorus is eliminated from detergents and 95 percent of the phosphorus is removed from all municipal and industrial wastes.

The second requirement is a basis of evaluating the probable effect on the lake if a program of phosphorus reduction were carried out. The recent work of Vollenweider (1968) on the role of phosphorus and nitrogen in the eutrophication of lakes provides the only basis for making this evaluation. Vollenweider made a comparison of all the world's lakes where reliable information was available on both phosphorus loading and the degree of eutrophication. The 20 lakes for which such information was available varied in area and depth. In order to compare these lakes of different area and volume, the loadings were expressed as the amount of phosphorus delivered to a unit surface area in a unit time (grams of total phosphorus per square metre of lake surface per year). Predicted effects were then evaluated as a function of the mean depth of the lakes.

Fig. 5.1.1 shows Vollenweider's evaluation of the effect of phosphorus loading and the degree of eutrophication. The two lines enclose the range of mesotrophic conditions. This area was defined on the basis of knowledge of the trophic conditions of various lakes involved. Three of the lakes - Léman, Bodensee (Constance) and Annecy - are definitely mesotrophic, while Lake Mendota was still rather mesotrophic in the early 1940's (the lower point). Lakes Sebasticook and Türler are slightly eutrophic, Vänern and Aegerisee are oligotrophic. The upward slope of the two lines enclosing the range of mesotrophy, is in good agreement with the accepted fact that the deeper the lake and the greater its volume, the greater is its capacity to absorb a given nutrient load.

The evaluation of the role of phosphorus in eutrophication is based on empirical rather than theoretical relationships. As such, it provides a solid basis for comparison which is free from assumptions. However, as Vollenweider points out, mean depth is the only parameter considered here in relation to phosphorus loading, and other factors (flushing

Table 5.1.1 Lake Erie: Annual input of total phosphorus (short tons/year).

Source		1967				Projected for 1986 without control measures		
Lake Huron		2,240				2,600		
	U.S.		Canada	Total	U.S.		Canada	Total
Detroit River								
Municipal	10,750		760	11,510	15,000		1,050	16,050
Industrial	350		630	980	1,000		1,580	2,580
Land drainage	1,490		1,380	2,870	1,600		1,500	3,100
Sub-Total		17,600				24,330		
Point Source								
Municipal	2,710		30	2,740	4,000		50	4,050
Industrial	Nil		20	20			50	50
Sub-Total		2,760				4,100		
Other Major Tributaries								
Municipal	4,360		480	4,840	8,000		1,050	9,050
Industrial	560		470	1,030	1,000		1,180	2,180
Land drainage	3,320		550	3,870	4,000		950	4,950
Sub-Total		9,740				16,180		
Total-Municipal & Industrial		21,120				33,960*		
Total-Other Sources		8,980				10,650		
TOTAL		30,100	(1.06 $g/m^2.yr$)			44,610	(1.57 $g/m^2.yr$)	
TOTAL - If by 1986 all phosphorus is eliminated from detergents and 95 percent removed from all municipal and industrial sources						11,160	(0.39 $g/m^2.yr$)	

*It is estimated that 70 percent of this will be from detergents.

Table 5.1.2 Lake Ontario: Annual input of total phosphorus (short tons/year).

Source	1967			Projected for 1968 without control measures		
Lake Erie						
Niagara River		4,500			6,700*	
	U.S.	Canada	Total	U.S.	Canada	Total
Niagara River						
Municipal	2,000	330	2,330	5,860	400	6,260
Industrial	150	80	230		210	210
Land Drainage	50	50	100		50	50
Unaccounted		540			600	
Sub-Total		7,700			13,820	
Point Sources						
Municipal	950	2,010	2,960	1,740	5,700	7,440
Industrial	Nil	180	180	20	460	480
		3,140			7,920	
Other Major Tributaries						
Municipal) Industrial)	920	1,200	2,120	2,500	2,000	4,500
Land Drainage	470	250	720	510	270	780
Sub-Total		2,840			5,280	
Total-Municipal & Industrial		7,820			18,890**	
Total-Other Sources		5,860			8,130	
TOTAL		13,680 ($0.65\ g/m^2.yr$)			27,020 ($1.29\ g/m^2.yr$)	
TOTAL - If by 1986 all phosphorus is eliminated from detergents and 95 percent removed from all municipal and industrial sources (including controls on Lake Erie).					3,400 ($0.17\ g/m^2.yr$)	

*Increased in proportion to projected 1986 loading to Lake Erie.
**It is estimated that 70 percent of this will be from detergents.

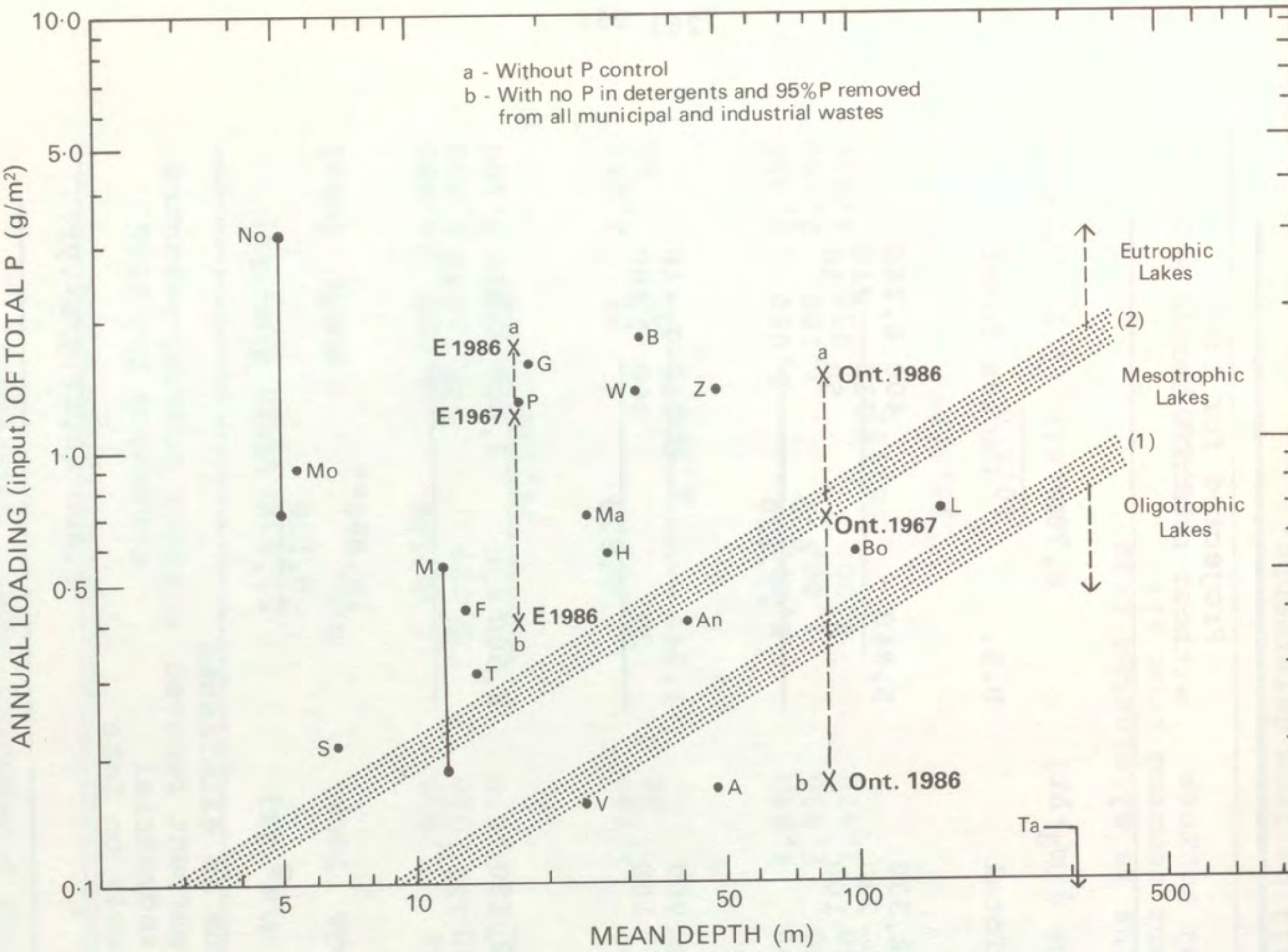

Fig. 5.1.1 State of eutrophication for a number of lakes in Europe and North America.

LEGEND

A - Aegerisee (Switzerland)
An - Lake Annecy (France)
B - Baldeggersee (Switzerland)
Bo - Lake Constance (Austria, Germany, Switzerland)
F - Lake Furesø (Denmark)
G - Greifensee (Switzerland)
H - Hallwillersee (Switzerland)
L - Lake Geneva (France, Switzerland)
M - Lake Mendota (U.S.A.)
Mä - Lake Mälaren (Sweden)
Mo - Moses Lake (U.S.A.)
No - Lake Norrviken (Sweden)
P - Pfäffikersee (Switzerland)
S - Lake Sebasticook (U.S.A.)
T - Türlersee (Switzerland)
Ta - Lake Tahoe (U.S.A.)
V - Lake Vänern (Sweden)
W - Lake Washington (U.S.A.)
Z - Zürichsee (Switzerland)
E - Lake Erie
Ont.- Lake Ontario

time, geographical location, etc.) must be considered. Also, the added effects of other nutrient substances and growth factors may be involved. For this reason, he emphasizes that the actual boundaries denoting the mesotrophic range as shown in Fig. 5.1.1 might be different for other lakes.

The relative position of points for some of the lakes in Fig. 5.1.1 strongly indicates that their mesotrophic boundaries must indeed be considerably different. For example, the relative distance above line (2) would indicate Lake Washington was more eutrophic than either Zürichsee or Lake Mendota. In fact, Lake Washington is considerably less eutrophic than either of these lakes.

In this regard it is interesting to note the relative position of the points describing the 1967 situations in Lakes Erie and Ontario. In Fig. 5.1.1, the upper X (1986) gives the projected loading in 1986 without any phosphorus control, and the lower X gives the projected 1986 loading if all phosphorus is eliminated from detergents and 95 percent of the phosphorus from all municipal and industrial wastes is removed. At the present time it is estimated that 50 to 70 percent of the total input of phosphorus from all municipal and industrial wastes into the lower Great Lakes comes from detergents. It is projected that this will become about 70 percent by 1986 if no controls are implemented.

Fig. 5.1.1 suggests that Lake Ontario is presently mesotrophic, in the upper range nearer to eutrophy. However, based on the various criteria examined earlier (Table 3.3.3, Lake Ontario Volume or Table 3.3.2, Lake Erie Volume) Lake Ontario actually seems to be much more oligotrophic or in a stage between oligotrophic and mesotrophic. If this is true, then elimination of phosphorus from detergents plus 95 percent removal of phosphates would return Lake Ontario to an oligotrophic range (Fig. 5.1.1). It seems very probable that this would indeed be the case.

Lake Erie is indicated as being rather highly eutrophic in 1967 from its position in Fig. 5.1.1. Also, it is suggested that it would still be well within the eutrophic range after elimination of phosphorus from detergents plus 95 percent removal of controllable phosphorus in 1986. As was found for Lake Ontario, the earlier examination of various criteria indicated that Lake Erie is considerably less eutrophic than Fig. 5.1.1 suggests. It thus seems more probable that the recommended phosphorus removal might well bring Lake Erie back down into the mesotrophic range. This assessment of Lake Erie is for the lake as a whole; regardless of phosphorus control the western basin will continue to be more eutrophic than the central and eastern basins.

Although Lake Erie has obviously undergone rapid eutrophication in recent years, it must be emphasized that it was not an oligotrophic lake before these recent changes. This can be inferred from the rather shallow depth, the rich soil and sedimentary rock drainage area, and the early history of a highly productive fishery. Even prior to recent changes, Lake Erie was probably a mesotrophic lake and any control measures applied will not alter its trophic condition below mesotrophy.

The conditions in the international section of the St. Lawrence River are largely dependent on the quality of water flowing out of Lake Ontario. Implementation of phosphorus control in the Lake Ontario basin would be sufficient to improve water quality in the St. Lawrence River. However, no increases should be allowed in the phosphorus loads discharged directly into the St. Lawrence River. Indeed some of these sources may need control to eliminate local nuisance conditions downstream from their points of entry.

In this consideration for phosphorus control, only detergents, municipal and industrial wastes have been considered as amenable to control. Further reductions in phosphorus input could be achieved with implementation of techniques to reduce the input from land drainage. There seems little doubt that a considerable input comes from agricultural lands. For example, it is estimated that more than 89,000 short tons of total phosphorus were contained in fertilizers applied to lands in the Lake Erie basin in 1966. If only 2 percent of this reached the waters of Lake Erie it would represent a substantial input. Control of such sources should be implemented as soon as possible. Implementation of this program in the Lake Erie basin would further reduce the input to Lake Ontario.

A good deal of concern is expressed about the regeneration of nutrients from the sediments of enriched lakes after the nutrient supply from controllable sources is cut off. Once a lake has become so productive that oxygen is exhausted from deep water during summer, chemical changes at the mud-water interface cause a release of nutrients into the water from the surface sediments. This has been estimated as 8 percent of the total phosphorus load for one small eutrophic lake (Vollenweider, 1968). Large lakes are believed to be proportionately less affected than small lakes, but Lake Erie, which already shows considerable oxygen depletion in the hypolimnion, is approaching this dangerous point in eutrophication. Prevention of this state would serve to delay the regeneration of another source of nutrient enrichment.

The recovery time for a lake to revert to a less eutrophic condition after reduction of nutrient input is very difficult to assess. It depends on how far the total nutrient load is reduced and the extent to which the remaining load is diluted. This in turn depends on the volume of water, area, thermal stratification and circulation, renewal of the lake volume, recycling of nutrients within the lake, and sediment-water exchange processes. The exchange between water and bottom sediments is primarily at the surface layer, at least in deep waters. If the external input of nutrients to the lake is drastically reduced, it will decrease the nutrient content of the surface sediments, and the amount of regeneration of nutrients from the mud.

If all phosphorus were removed from detergents and 95 percent removed from municipal and industrial wastes by 1986, the total phosphorus loading to Lake Erie in 1986 would be only 37 percent of what it was in 1967. Although there are no data on the total loading to Lake Erie in earlier years, there is evidence that mean phosphorus levels in the western basin increased about threefold from 1942 to 1967. With the not unreasonable assumption that this reflects the proportional change in phosphorus loading, it suggests that the conditions in Lake Erie might eventually be restored to those of the early 1940's.

The evaluation of the probable effects of phosphorus removal is the best assessment that can be made with our present knowledge. Perhaps the most difficult question to answer is whether or not eutrophication can be controlled by the reduction of phosphorus alone. All evidence suggests that it can. Phosphorus removal is the only economically feasible solution at the present time, and it is the logical place to start in a series of accessory remedial measures that may ultimately be necessary if population and technological growth in the Great Lakes basin continue without limit. Thus, it is not claimed that phosphorus removal will control all the problems of the future; only that it is the best known remedial measure at present and one that must be accepted as the basis for all future controls. Treatment for removal of nitrogen compounds may have to be instituted in the future.

Encouragement can be taken from the fact that phosphorus removal as a remedial measure is now being undertaken at the very eutrophic Swiss lake, Zürichsee, where 55 percent of the phosphorus loading comes from controllable sources (Fig. 5.1.1). Phosphorus removal is also being undertaken in Sweden. If phosphorus is as important as believed, then the results of the recent sewage diversion from Lake Washington (Fig. 5.1.1) are also most encouraging (about 50 percent of the phosphorus loading came from sewage). Lake Washington has already shown dramatic recovery to a much less eutrophic condition since the diversion was completed little more than a year ago.

In the recommendations to the International Joint Commission with respect to phosphorus reduction in municipal wastes it should be understood that two concurrent steps are proposed to control cultural eutrophication in the lakes: firstly, that phosphates must be replaced in detergents with an environmentally acceptable substitute and secondly, that the load remaining in municipal wastes after phosphate removal from detergents must be reduced by 80 percent. This will amount to an overall reduction in present municipal waste loads of 95 percent, and that by 1986, municipal waste reduction of phosphates is to be further increased from 80 to 95 percent at the treatment plants.

5.2 MUNICIPAL AND INDUSTRIAL WASTE TREATMENT

Remedial measures are required to reduce the fertilization and resulting adverse effects on water quality from nuisance biological growths by implementing phosphorus removal or control at waste water sources and other locations.

These measures include immediate reduction and eventual replacement of phosphorus in detergents and implementation of programs for the reduction of phosphorus in municipal and industrial waste effluents. The municipal and industrial pollution control effort should be guided by the limits set out in the basis of recommendations for control of phosphorus inputs to the lower lakes and their connecting rivers.

As previously indicated, a very high degree of phosphorus removal will be required in Lake Erie to arrest the rate of eutrophication and improve lake water quality. For this reason, all feasible approaches to the phosphorus removal problem must be implemented. The question may be raised as to why it is necessary to remove phosphorus both from detergents and at sewage treatment plants.

The first concerns timing. Partial replacement of phosphates in detergents is now possible with no reduction in cleansing power. Also if urgency is attached to finding an environmentally harmless substitute for full replacement of phosphates, it might be possible to find an answer within a few years. As seen from the dates recommended in Section 1.2

(Volume 1) for sewage plant nutrient removal, it will be economically and physically impractical to have full facilities completed for Lake Erie and its tributaries before 1975 and for Lake Ontario before 1978. If the technology for detergent phosphate removal can be quickly developed, an almost immediate elimination of a substantial proportion of the phosphorus loading to Lake Erie and Lake Ontario could be achieved to prevent further deterioration of these lakes while sewage treatment facilities are being built.

Secondly, the requirement of phosphorus removal would in many cases impose undue financial burdens on small municipalities, individual homes and industries in the drainage basins. In such cases treatment facilities cannot be economically provided, other than by reduction of the phosphorus contributed by detergents. An added benefit from a program of phosphate removal from detergents would be a significant reduction in the rate of fertilization and eutrophication of inland lakes and rivers in the drainage basin of the Great Lakes, improving their quality for recreational, domestic and other uses.

Thirdly it is estimated that treatment costs for phosphate removal at sewage treatment plants would be reduced by a half to two-thirds by removal of phosphates from detergents. At the present time 70 percent of the phosphorus in municipal sewage in the United States and 50 percent in Canada arises from phosphate-based detergents, the overall basin average lying close to that of the United States. The current average content of phosphorus in sewage is about 10 mg/l, of which 7 mg/l originates from detergents. If phosphates were replaced in detergents, removal of 80 percent of the remaining phosphorus at the sewage treatment plant would then reduce the concentration to 0.6 mg/l. To achieve the same effluent concentration without replacement of phosphates in detergents would require more than 95 percent removal at the sewage treatment plant with two to three times the overall cost, largely due to the additional chemicals needed and solid wastes produced. Since solution of the combined sewer overflow problem will take a number of years to accomplish, an early reduction in phosphorus inputs to the lakes from this source could be achieved by detergent reformulation.

The two remedial measures should be thought of as complementary since detergents and human wastes are the principal sources of phosphorus to the lakes. For these reasons both measures should be instituted as recommended.

Water pollution control should be treated like any other public utility, the purpose of which is to serve the public with the best and most efficient service. Greater attention should be given to providing standby equipment capable of preventing water pollution during periods of breakdown or inadequate performance. The need exists for municipalities to extend the policy of separating combined storm and sanitary sewage collection systems in newly developed areas to include the correction of existing combined sewer systems. In existing combined sewered areas, where separation is not economically feasible, municipalities should provide for control of pollution resulting from overflows of these systems.

There are several municipal locations where basic sewage service is still lacking and sewage treatment is needed (Table 3.1.1). Nutrient removal will probably become a universal requirement throughout the Great Lakes basin as the density of urban development increases. Priorities should be established to attack initially the major sources of the problem.

The principal industries contributing direct discharges of wastes to the lakes are listed in Tables 3.1.2 and 3.1.3, Lake Erie. In a number of cases their waste recovery and/or treatment programs are inadequate to protect the quality of lake waters. Accelerated industrial remedial programs are required to control oxygen-consuming materials, organic substances, acids, alkalis, iron, phenols, oils and toxic substances.

5.3 CONTROL OF POLLUTION FROM LAND DRAINAGE

Measures are required to reduce the amount of phosphorus lost from the lands of the drainage basins of the lower Great Lakes. This will require improved control of animal waste disposal, soil and riverbank erosion by those responsible for livestock and land management. Water pollution control agencies should ensure that appropriate action is taken to reduce the input of phosphorus from these sources by encouraging government agencies to develop and implement plans directed toward this objective. These measures should include improved practices of soil fertilization, land tilling and conservation activities. A system of inventory and improved techniques for the application of toxic pesticides and herbicides to field crops should be developed at the earliest opportunity. Substitutes should be found for persistent toxic chemicals and their use encouraged.

5.4 OIL AND INDUSTRIAL MATERIAL SPILLS

An international program is required to cope with oil, industrial or toxic spills on the Great Lakes whether such incidents are considered as catastrophes, or less spectacular events. The essential elements of the program must recognize prevention, surveillance, notification, and cleanup.

Contingency plans, which are essentially procedural arrangements for the notification and cleanup of spilled pollutants, have been developed in the United States for the Great Lakes basins by the Federal Water Pollution Control Administration. These plans are extensive and have been developed to the point that a significant response capability is now available. Development of similar plans has been initiated in Canada, and as details are worked out coordination of the international aspects of such plans should be provided by the International Joint Commission.

Water quality objectives and their enforcement are the most effective methods of preventing pollution of a continuing nature. Pollution prevention programs should include a requirement by governments to have all those who handle, process, transport and dispose of materials which may cause water pollution, examine their existing facilities, procedures, personnel training and operations to prevent spills and other pollution incidents.

Immediate reporting is essential in the case of a sudden pollution incident. A proper surveillance and reporting system is necessary to effectively organize countermeasures and minimize pollution damages. Existing legislation should also be reviewed at all levels of government to ensure that in the event of danger of pollution from a recurring or non-recurring source, the authority exists for undertaking adequate measures to abate pollution either by the parties concerned, or the appropriate governments if the parties fail to do so.

The first step in any effective cleanup program on the Great Lakes should be to develop an international contingency plan. Such planning must recognize the problems at all levels: local, regional, state, provincial, national and international. The plan must also involve those agencies which have the technical and scientific personnel trained and located to handle the problems. This may require the integration of resources, manpower, materials, equipment and technology in both countries.

The contingency plan and prevention measures although directed primarily to oil spills and disasters should also encompass the handling, storage and transfer of hazardous substances whether by ship, rail or road. Cargo tonnages now transported on the Great Lakes are expected to increase substantially by the turn of the century. It is not unreasonable to expect that a part of the increase might include oil. Therefore, consideration should be given now by the appropriate regulatory agencies to the increased potential of pollution from this source.

5.5 OTHER SOURCES

5.5.1 Vessel Wastes

Compatible rules and regulations governing all types of waste discharges from vessels and boats are required. Local, provincial, state and federal governments concerned with water pollution control and the licensing and registering of all commercial and recreational vessels should develop these rules and regulations to be effective no later than 1970. The agreements should not preclude interim measures that might be promulgated and made effective by any local, state or provincial governments prior to 1970.

The rules and regulations should include all forms of pollutants that might be discharged from any type of vessel or boat using the international waters between the United States and Canada. Of particular concern are discharges of sewage, ballast, bilge water, waste oils, garbage, litter and related solids.

5.5.2 Thermal Wastes

Plans and programs for the location and operation of thermal power plants, including conventional and nuclear-fueled generating stations on the Great Lakes should recognize both the potential benefits and adverse effects of waste heat.

5.5.3 Radioactivity

Radioactive wastes, discharged directly to the lakes or their tributaries from nuclear reactors, waste processing plants, industrial, medical and research centres, are presently monitored by federal, state and provincial authorities. Such wastes should continue to be controlled and monitored.

A lake surveillance program should be implemented for observance of total levels of radioactivity. The need for contingency plans must be recognized in advance of a serious accident or undesirable radioactive levels in the lakes.

5.5.4 Dredging

The disposal of dredged material containing objectionable quantities of pollutants should be undertaken in such a manner that the materials will not damage the quality of waters and wildlife feeding areas in Lakes Erie and Ontario.

5.5.5 Solid Wastes

Solid wastes, some of which contain garbage, metals, oil and other deleterious substances, should be disposed of in areas or containments where there can be no adverse effects on water quality. Shore improvements and other construction operations which utilize refuse or other deleterious materials or wastes should not be permitted, unless authorization has been granted by the appropriate authorities.

5.6 SUMMARY

The foregoing chapters describe the intensification of the pressures responsible for water pollution in the Lake Erie basin. The projections of population growth and industrial developments indicate a probable doubling by 1986 of the raw waste loadings produced by municipalities and industries. Land drainage has been cited as causing significant pollution problems but practical control measures are not yet readily available. Waste heat and losses of oil and industrial materials are not new problems, however, their magnitude has grown. It is clear that future requirements for cooling water and the discharge of large quantities of waste heat will pose serious questions on how to protect or preserve the ecological environments of nearshore waters. Industrial growth and increasing vessel traffic in the Great Lakes will create further potential hazards for spills of oil and hazardous materials unless precautions are taken to prevent such occurrences.

If water level regulations are instituted in Lake Erie changes in water quality in western Lake Erie may make it necessary to impose stricter regulations on waste discharges than those in existence today or presently programmed.

Improvement in the quality of water can be expected with phosphorus reduction in the drainage basin provided that the recommended implementation programs are developed and carried through by municipalities and industry. To be effective these programs must cope not only with existing sources of nutrients but the increasing amounts that will be wasted in the waters of the drainage basin. Waste treatment facilities must be designed to satisfy needs for the next fifteen to twenty years to meet the waste loading projections for the mid 1980's.

The principles that have evolved in dealing with the complexity of water use and quality control of river systems are applicable to the Great Lakes. At one time, the general rule was that the downstream owner had the right to enjoy the flow of water in its natural state (Gross, 1965). It was subsequently recognized that the public interest might best be served by yielding the private rights of the downstream proprietor. Lyon (1968) drew attention to the case where the downstream use was in the public interest, often involving public water supply. In this case, the public use deserved precedence over the upstream waste discharge. In recent years, water pollution control laws have been enacted to protect a variety of public interests involving many water uses.

At one time abatement plans were relatively simple involving merely single pollution sources, whereas, in many cases today, multiple sources of pollution having a cumulative effect on water quality are common. Thus, the effect of any one discharge is not readily discernible, and minimum degrees of treatment (primary or secondary) may not be adequate to protect water uses. In these situations, comprehensive systems analysis should be used to deal with the complexities of the problem and waste load allocations made among the water users. The latter approach is required to deal with both existing and developing water quality problems of the Great Lakes especially in those areas of intensive water use.

In order to protect water uses that may interfere increasingly with one another improved water quality criteria have been needed. These criteria are set forth to determine the desired quality for future uses of water as the standards and objectives for Lake Erie and Lake Ontario.

5.6.1 Water Quality Objectives

Although water quality objectives or standards have been established for the waters of Lake Erie, Lake Ontario and the international section of the St. Lawrence River by provincial and state authorities, it is desirable that the International Joint Commission develop objectives for its use in administering the Boundary Waters Treaty.

Water quality objectives should be designed to provide suitable water quality for present and future beneficial use of the waters. Uses which should be considered are:

(a) domestic water supply

(b) propagation of aquatic life and wildlife

(c) recreation and aesthetics (including body contact and pleasure boating)

(d) agriculture (including irrigation and stock watering)

(e) industrial supply (including process and cooling waters, and power generation)

(f) commercial shipping.

Water quality objectives should apply to the receiving waters since it is the quality of the lake waters that is important. Regulation of waste discharges to assure compliance with the objectives will involve the setting of effluent controls and monitoring of waste discharges by the provincial and state pollution control agencies. A review of objectives will also be required to meet the demands and requirements of population and industrial growth and technological changes in industry and waste treatment processes.

General Objectives

These general objectives should apply to all waters at all places and at all times;

(a) free from substances attributable to municipal, industrial or other discharges that will settle to form putrescent or otherwise objectionable sludge deposits, or that will adversely affect aquatic life or waterfowl.

(b) free from floating debris, oil, scum and other floating materials attributable to municipal, industrial or other discharges in amounts sufficient to be unsightly or deleterious.

(c) free from materials attributable to municipal, industrial or other discharges producing colour, odour, or other conditions in such degree as to create a nuisance.

(d) free from substances attributable to municipal, industrial or other discharges in concentrations that are toxic or harmful to human, animal, or aquatic life.

(e) free from nutrients derived from municipal, industrial and agricultural sources in concentrations that create nuisance growths of aquatic weeds and algae.

Specific Objectives

The specific objectives listed below are for evaluation of conditions in the waters of the lower Great Lakes other than areas in proximity to outfalls where mixing zones should be prescribed by pollution control agencies.

The parameters selected are intentionally limited to those believed to be most meaningful in relation to International Joint Commission responsibilities. The recommended objectives are designed to protect international waters for the most sensitive use in each case.

(a) Microbiology (Coliform Group) - The geometric mean of not less than five samples taken over not more than a 30-day period shall not exceed 1,000/100 ml total coliforms, nor 200/100 ml fecal coliforms in local waters.

Water used for body contact recreation activities should be free from bacteria, fungi, or viruses that may produce enteric disorders, or eye, ear, nose, throat and skin infections.

Discussion: Where ingestion is probable, recreational waters can be considered impaired when the above criteria are exceeded. As a general rule, the waters of international significance will be protected and maintained if local water quality conditions meet these microbiological objectives or standards. The International Joint Commission adopted an objective for bacteria in the Boundary Waters (Connecting Channels) in which the coliform median value, MPN (most probable number) was not to exceed 2400/100 ml (International Joint Commission, 1950 and 1951).

(b) Dissolved Oxygen - Neither less than 6.0 mg/l at any time in epilimnetic (upper) waters nor in concentrations which would adversely affect cold water species in hypolimnetic (lower) waters.

Discussion: The objective is established to support fish and their associated biota, particularly cold water species.

(c) Total Dissolved Solids - Not more than 200 mg/l.

Discussion: The total dissolved solids concentration is a gross indicator of water quality, and is approaching the 200 mg/l level, which indicates the need for immediate action to reduce inputs of dissolved materials. Dissolved solids become important to domestic and industrial water supplies at about 500 mg/l.

(d) Temperature - No change which would adversely affect beneficial use.

Discussion: It is not considered practicable at this time to establish absolute limits, due to the lack of adequate information on the effects of temperature changes in the referenced waters.

(e) Taste and Odour - Virtually no taste or odour.

Phenols - Not to exceed a monthly average value of 1.0 µg/l. It would be desirable to obtain even lower concentrations.

Discussion: The effectiveness of conventional water treatment in removing odour from public supplies is highly variable depending on the nature of the material causing the odour. Tainting of fish flesh may result from materials not adequately removed by waste treatment processes. It is desirable that odour and taste producing materials be virtually absent. The International Joint Commission adopted an objective for phenols in the Boundary Waters (Connecting Channels) in which the average value was not to exceed 2.0 µg/l. The objective for taste and odour called for a threshold number of 8 or less (International Joint Commission, 1950 and 1951).

(f) pH - No change from present levels.

Discussion: Present levels are considered to be within the desirable range, falling within the objectives for the Boundary Waters (Connecting Channels): "The pH of these waters following dilution is to be not less than 6.7 nor more than 8.5." (International Joint Commission, 1950 and 1951).

(g) Iron - Not to exceed 0.3 mg/l.

Discussion: The objective conforms to the United States Public Health Service drinking water standards (United States Public Health Service, 1962) and the Canadian drinking water standards and objectives (Department of National Health and Welfare, 1969) for protection of public water supplies. This value is the same as the Connecting Channels objective for iron as set forth in the 1950 report.

(h) Phosphorus - Concentrations should be limited to the extent necessary to prevent nuisance growths of algae, weeds and slimes which are or may become injurious to water use.

Discussion: Phosphorus, which under certain conditions stimulates nuisance growths of algae, weeds, and slimes, is considered to be susceptible to control. It has been found that algal blooms can be expected to follow in years when the concentration of inorganic phosphorus and inorganic nitrogen exceed 10 and 300 μg/l, respectively, at the time of spring turnover.

Reduction of phosphorus inputs to the lower lakes is the only method currently available for controlling the rate of eutrophication. It is expected that phosphorus control would result in a return to a condition of mesotrophy for Lake Erie as a whole, and a condition of oligotrophy for Lake Ontario.

(i) Radioactivity - Gross Beta - not to exceed 1000 pCi/l

Radium-226 - not to exceed 3 pCi/l

Strontium-90 - not to exceed 10 pCi/l.

Discussion: Objectives were established to conform to United States Public Health Service drinking water standards, for protection of public water supplies.

5.6.2 Revision of Water Quality Objectives for the Connecting Channels

Since the Connecting Channels have a profound effect on the water quality of the lower lakes it is recommended that the Advisory Boards for the Connecting Channels develop revised water quality objectives for adoption by the International Joint Commission. Their objectives should be compatible with those set out in this report for the lower lakes.

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APPENDIX

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[illegible]	Marine Sciences Branch, Department of Energy, Mines and Resources, Ottawa, Ontario.

APPENDIX

METHODS OF MEASUREMENT

INTRODUCTION

Chemical, bacteriological, biological, physical and sedimentological methods are reported and referenced in this Appendix. This is followed by a description of the methodology for materials balance and annual input of total-phosphorus projected to 1986.

Chemical methods have changed significantly over the years, so that comparisons in the report between recent and earlier chemical determinations although accurate enough to indicate general trends, are not highly precise. In any one year reported on in this study, data from only one, or at most two, laboratories were used, so that spatial and time comparisons during the year are valid.

Some of the chemical analyses may have been affected by changes occurring in storage of the samples, and interference in the colorimetric methods arising from sample turbidity. Reliable and well established methods exist for many constituents but for most, new techniques are evolving rapidly. Colorimetric methods, for example, are being automated to permit high sampling rates, and new techniques such as atomic absorption spectrophotometry are becoming available.

PARTICIPATING AGENCIES

EMR	Dept. of Energy, Mines and Resources
FRB	Fisheries Research Board
FWPCA	Federal Water Pollution Control Administration
LEBO	Lake Erie Basin Office (Cleveland)
LOBO	Lake Ontario Basin Office (Rochester)
GLI	Great Lakes Institute - University of Toronto
NHW	Dept. of National Health and Welfare
OWRC	Ontario Water Resources Commission

CHEMICAL METHODS FOR LAKE WATER AND RIVER WATER

ALKALINITY

The unit for alkalinity used in this report is reported as mg $CaCO_3/l$. The constituents reacting with hydrogen ion during the alkalinity measurement were assumed to be CO_3^{-2}, and an equivalent amount of Ca^{++} was arbitrarily assumed to be present. Actually most of the alkalinity in Great Lakes waters is HCO_3^-. The conversion factor for alkalinity is 1 mg $CaCO_3/l$ = 1.219 mg HCO_3^-/l.

FWPCA, 1965, 1967 and 1968 and EMR, 1966 and 1967

An indicator solution of bromcresol green + methyl red was added, then the sample was titrated with 0.02 normal sulphuric acid until the colour changed from blue to pink at a pH of 4.6 (American Public Health Association, 1965).

NHW, 1966

Samples were mixed with a buffered acidic methyl orange indicator solution and the final colour was measured at 550 millimicrons, in an Auto-Analyzer. Standard solutions contained sodium bicarbonate (Ad Hoc Working Committee on Methodology, 1968).

AMMONIA

FWPCA (LOBO) 1965 to 1967

The technicon Auto-Analyzer was used for most NH_3-N and organic N tests. Both of the following methods were used simultaneously.

a) Samples with adjusted pH to 9.5 with buffer were distilled into 2 percent boric acid. An aliquot was Nesslerized and colour development in samples compared with a blank and standards (American Public Health Association, 1965).

b) Filtered samples were mixed with sodium hydroxide + phenol + sodium hypochlorite + sodium nitroprusside. The mixture was passed through a 38°C heating bath and the resulting colour measured at 630 millimicrons in an Auto-Analyzer. A trap containing sulphuric acid isolated the reagents from ammonia in the laboratory air (Ad Hoc Working Committee on Methodology, 1968).

NHW, 1967 and FWPCA (LEBO) 1965, 1967 and 1968

Unfiltered samples were mixed with sodium hydroxide + phenol + sodium hypochlorite + sodium nitroprusside. The mixture was passed through a 38°C heating bath and the resulting colour measured at 630 millimicrons in an Auto-Analyzer. A trap containing sulphuric acid isolated the reagents from ammonia in the laboratory air (Ad Hoc Working Committee on Methodology, 1968).

OWRC, 1964 to 1967

The direct Nesslerization method was used. Zinc sulphate was added to the sample, then sodium hydroxide was added to give a pH of 10.5, then Nessler reagent (potassium iodide + mercuric chloride + potassium hydroxide) was added, and the resulting colour measured at 410 millimicrons (American Public Health Association, 1955).

BIOCHEMICAL OXYGEN DEMAND

NHW and EMR, 1966

Samples were stored for a few hours to attain laboratory temperature. Air was then bubbled through each sample to produce oxygen concentrations near equilibrium values. Two 300 ml BOD bottles were filled from each sample through a siphon. Dissolved oxygen in one of the BOD bottles was measured immediately. The other bottle was stored in the dark at 20°C for five days, and its final oxygen concentration measured. A water seal was maintained around the top of the bottle during incubation. Dilution and seeding procedures were not required (American Public Health Association, 1965).

OWRC and FWPCA 1965, 1967 and 1968

In the period 1964 to 1966, initial and final oxygen values were determined by the azide modification of the Winkler method (American Public Health Association, 1960). From 1967 on, oxygen values were determined by polarography (American Public Health Association, 1960).

CHLORIDE

FWPCA, 1965, 1967 and 1968 and EMR, 1966

An indicator reagent, containing s-diphenyl-carbazone + enough nitric acid to give a pH of 2.5 ± 0.1, + xylene cyanol FF + ethyl alcohol, were added to the sample. The mixture was titrated with mercuric nitrate to a purple endpoint, Standard Methods, Twelfth Edition (American Public Health Association, 1965).

NHW, 1966 and EMR, 1967

Unfiltered samples were mixed with ferric ammonium sulphate + nitric acid + mercuric thiocyanate. The resulting colour was measured at 505 millimicrons in an Auto-Analyzer (Ad Hoc Working Committee on Methodology, 1968).

OWRC, 1964 to 1967

Initially, the Mohr titration method was used (American Public Health Association, 1955) but later, samples were simply titrated with silver nitrate using a Fisher automatic titration unit and a chloride-sensing electrode.

CONDUCTIVITY

OWRC, 1964 and FWPCA 1965, 1967 and 1968

The electrical conductivity and temperature of the sample were measured at room temperature (20 to 30°C) and the conductivity at 25.0°C calculated using the temperature-conductivity relationship of 0.01 normal potassium chloride (American Public Health Association, 1965).

HARDNESS (CALCIUM + MAGNESIUM)

FWPCA (LOBO) and EMR, 1966

The sample was titrated with a magnesium salt of EDTA using eriochrome black T indicator, the solution turning from wine red to blue when all the magnesium and calcium ions are complexed (American Public Health Association, 1965).

NHW, 1966 and FWPCA (LEBO) 1965, 1967 and 1968

The sample was mixed with disodium magnesium EDTA and disodium EDTA, then with pH 10.3 buffer (ammonium chloride + ammonium hydroxide) and Eriochrome Black T. The resulting colour was measured at 520 millimicrons (Ad Hoc Working Committee on Methodology, 1966).

EMR, 1967

Total hardness was computed from the results of calcium and magnesium obtained by atomic absorbtion spectrophotometry.

NHW, 1967

The sample was mixed with disodium magnesium EDTA + disodium EDTA + pH 10.3 buffer + Calmagite. The resulting colour was measured at 520 millimicrons (Ad Hoc Working Committee on Methodology, 1968).

IRON

FWPCA, 1965

The sample was boiled in the presence of hydrochloric acid + hydroxylamine. A buffer solution of ammonium acetate + acetic acid was added to give a pH of 3.2, then phenanthroline was added. The resulting colour was measured at 510 millimicrons (American Public Health Association, 1965).

TOTAL BIOLOGICALLY AVAILABLE IRON

NHW, 1967 and EMR, 1967

An unfiltered sample was mixed with hydrochloric acid, hydroxylamine hydrochloride, 2, 4, 6-tripyridyl-s-triazine, and (sodium acetate + acetic acid) buffer. The mixture was then passed through a 37°C heating bath. The resulting colour was measured at 600 millimicrons in an Auto-Analyzer (Ad Hoc Working Committee on Methodology, 1968).

NITRATE

FWPCA (LOBO)

The Brucine method was used (American Public Health Association, 1965).

OWRC, 1964 to 1967

A phenoldisulphonic acid method was used, without correction for chloride concentration (American Public Health Association, 1955).

NITRITE

OWRC, 1964 to 1967

Sulphanilic acid + hydrochloric acid were added; then α-naphthylamine hydrochloride + hydrochloric acid, and sodium acetate. The resulting colour was measured at 520 millimicrons (American Public Health Association, 1955).

NHW, 1966

Nitrite in unfiltered samples was measured after adding sodium hydroxide + ortho-phosphoric acid + sulphanilamide + N-(1-naphthyl) ethylenediamine dihydrochloride. The resulting colour was measured at 520 millimicrons in an Auto-Analyzer (Ad Hoc Working Committee on Methodology, 1966).

NHW, 1967

Nitrite in unfiltered samples was measured using an Auto-Analyzer. Sulphanilamide, hydrochloric acid, and N-(1-naphthyl) ethylenediamine dihydrochloride were mixed with the sample and the resulting colour measured at 550 millimicrons (Ad Hoc Working Committee on Methodology, 1968).

NITRATE + NITRITE

FWPCA, 1967 to 1968
(Sum of Nitrate + Nitrite reported as Nitrate)

Nitrate was reduced to nitrite in a zinc column buffered with sodium acetate and hydrochloric acid. The diazonium salt was produced by reacting nitrite with sulphuric acid. The diazonium salt formed an azo dye when reacted with 1 - naphthylamine hydrochloride. An Auto-Analyzer was used to measure the absorbance at 520 millimicrons.

NHW, 1966

Samples were not filtered. Nitrate was reduced to nitrite by adding sodium hydroxide, hydrazine sulphate, and copper sulphate. The mixture was passed through a 38°C heating bath. Total-nitrite was measured by adding orthophosphoric acid + sulphanilamide + N-(1-naphthyl) ethylenediamine dihydrochloride, and measuring the resulting colour at 520 millimicrons in an Auto-Analyzer (Ad Hoc Working Committee on Methodology, 1966).

NHW, 1967 and EMR, 1967

Unfiltered samples were analyzed using an Auto-Analyzer. Nitrate was reduced to nitrite by adding EDTA and passing the mixture over cadmium filings. Total nitrite was then measured by adding sulphanilamide and N-(1-naphthyl) ethylenediamine dihydrochloride, and measuring the resulting colour at 550 millimicrons (Ad Hoc Working Committee on Methodology, 1968).

TOTAL-KJELDAHL NITROGEN (AMMONIA + ORGANIC NITROGEN)

FWPCA (LOBO), 1965 to 1967

Unfiltered samples were digested using potassium persulphate digestion. The ammonia liberated was Nesslerized and measured at 425 millimicrons. An alternate method utilized an automated alkali phenol nitro-pruisside procedure on an Auto-Analyzer preceeded by digestion with sulphuric acid and potassium persulphate.

OWRC, 1964 to 1967 and FWPCA (LEBO) 1964, 1967 and 1968

Sulphuric acid and copper sulphate were added, and the organic nitrogen digested by boiling. The solution was made alkaline with sodium hydroxide. The solution was then distilled and Nessler reagent (potassium iodide + mercuric chloride + potassium hydroxide) added. The colour was compared with Tintometer glass disc standards.

NHW, 1967

Unfiltered samples were digested and then analyzed for total ammonia, using an Auto-Analyzer for both steps. Selenium dioxide + sulphuric acid + perchloric acid were added. The mixture was heated to 380°C. After digestion, the mixture was neutralized with sodium hydroxide. Ammonia was measured by adding alkaline phenol + sodium hypochloride + sodium nitroprusside, and measuring the resulting colour at 630 millimicrons (Ad Hoc Working Committee on Methodology, 1968).

DISSOLVED OXYGEN

FWPCA and NHW, 1965 and
M/V "Theron" on Lake Ontario, 1967

The Winkler iodometric method was used. Two millilitres of each reagent were added to each sample. The alkaline iodide reagent contained 150 grams of potassium iodide and 10 grams of sodium azide per litre (American Public Health Association, 1965).

EMR, M/V "Brandal" 1966; M/V "Theron" 1968

The Winkler iodometric method was used. One millilitre of each reagent was added to each sample. In 1966 the alkaline iodide solution contained 700 grams potassium hydroxide and 150 grams potassium iodide per litre. From 1967 the Pomeroy-Kirschman reagent, containing 400 grams sodium hydroxide and 900 grams sodium iodide per litre, was used (Ad Hoc Working Committee on Methodology, 1968).

pH AT LABORATORY TEMPERATURE

EMR (M/V "Brandal") 1966 and 1967

Samples were analyzed about 10 to 20 hours after sampling. Changes in pH during the storage interval limited the accuracy of the data to about ± 0.1 to 0.3 pH units. The pH was measured using a Corning Model 10 meter, and glass and reference electrodes, calibrated with pH 7.4 (phosphate) and pH 9.2 (borax) standard solutions (Ad Hoc Working Committee on Methodology, 1966).

FWPCA (LOBO) 1965

Beckman zeromatic pH meter with temperature adjustment.

PHENOL AND RELATED SUBSTANCES

NHW and FWPCA from 1966

The pH of the sample was adjusted to 4.0 by adding ortho-phosphoric acid. Copper sulphate was added and the sample distilled. Phenol in the distillate was measured by adding ammonium chloride, ammonium hydroxide to produce a pH of 10.0 ± 0.2, and finally 4-aminoantipyrine and potassium ferricyanide. The resulting colour was extracted into chloroform and measured at 460 millimicrons (American Public Health Association, 1965).

OWRC, 1964 to 1967

A preliminary distillation step was omitted for most samples. A buffer solution with pH 9.3, and containing sodium arsenite was added, then Gibbs reagent (2, 6 - dibromoquinonechlorimide and ethyl alcohol) were added, and finally n-butyl alcohol. The colour in the butanol layer was compared visually with a series containing known amounts of phenol.

ORTHOPHOSPHATE-PHOSPHORUS

FWPCA (LOBO)

Stannous chloride method was used on an unfiltered sample and colour was measured photometrically at 690 millimicrons (American Public Health Association, 1965).

NHW, 1966

Phosphate in unfiltered samples was measured by adding ammonium molybdate + hydrochloric acid + stannous chloride. The resulting colour at 660 millimicrons in an Auto-Analyzer (Ad Hoc Working Committee on Methodology, 1966).

SOLUBLE ORTHOPHOSPHATE-PHOSPHORUS

EMR, 1967

The method utilized an ammonium molybdate-antimonyltartarate/ascorbic acid reduction with an isopropyl alcohol extraction. Determinations were made spectrophotometrically.

NHW, 1967

Samples were filtered through a 5 micron membrane filter that had been previously washed with hydrochloric acid. Phosphate was measured by adding sulphuric acid + ammonium molybdate + potassium antimonyl tartrate + ascorbic acid, passing the mixture through a 70°C heating bath, and measuring the resulting colour at 660 millimicrons in an Auto-Analyzer (Ad Hoc Working Committe on Methodology, 1968).

OWRC, 1964 to 1967 and FWPCA

Samples were filtered, then ammonium molybdate + sulphuric acid, and stannous chloride + hydrochloric acid were added. The colour that developed was measured at 690 millimicrons (American Public Health Association, 1955).

TOTAL-PHOSPHORUS

FWPCA (LOBO)

Unfiltered samples were digested with sulphuric acid and potassium persulphate and the analyzed using the stannous chloride method used for orthophosphate-phosphorus (American Public Health Association, 1965).

NHW, 1967 and FWPCA (LEBO) 1965, 1967 and 1968

Samples were digested with sulphuric acid + potassium persulphate + heat, then neutralized with sodium hydroxide. Sulphuric acid + ammonia molybdate + potassium antimonyl tartrate + ascorbic acid were added passing the mixture through a 70°C heating bath. The resulting colour was measured at 660 millimicrons in an Auto-Analyzer (Ad Hoc Working Committee on Methodology, 1966, 1968).

OWRC, 1964 to 1967

Samples were treated with perchloric acid + heat. Phosphate was measured by adding ammonium molybdate + sulphuric acid, and stannous chloride + hydrochloric acid. The resulting colour was measured at 690 millimicrons (Ad Hoc Working Committee on Methodology, 1966; American Public Health Association, 1955).

SOLUBLE PHOSPHORUS

FWPCA, 1965, 1967 and 1968

The sample was filtered through Whatman filter paper #9 and treated as in total-phosphorus in the FWPCA analysis.

REACTIVE SILICATE

NHW, 1967 and FWPCA

Silicate in unfiltered samples was measured using an Auto-Analyzer, by adding ammonium molybdate + sulphuric acid + oxalic acid + sodium bisulphite + sodium sulphite + 1-amino-2-naphthol-4-sulphonic acid. The resulting colour was measured at 660 millimicrons (Ad Hoc Working Committee on Methodology, 1968).

OWRC, 1964 to 1967

Samples were dried at 103°C, and the residue cooled and weighed (American Public Health Association, 1960).

NONFILTERABLE RESIDUE (TOTAL SUSPENDED MATTER)

OWRC, 1964; NHW, 1966 and FWPCA, 1965, 1967 and 1968

The sample was filtered through a preweighed glass fibre filter. The filter was then dried at 103°C and weighed (American Public Health Association, 1960).

TURBIDITY

EMR and NHW, 1966 and FWPCA, 1965, 1967 and 1968

Turbidity was measured with a Hellige turbidimeter.

EMR and NHW, 1967

Turbidity was measured with a Hach Model 1860 turbidimeter.

BACTERIOLOGICAL METHODS FOR LAKE AND RIVER WATER

UNITS FOR BACTERIOLOGICAL DATA

Colonies per 100 millilitres is the unit used for reporting the bacteriological data. The Standard Plate Count unit is given as colonies per millilitre.

BACTERIOLOGICAL SAMPLING

NHW, M/V "Brandal" and "Theron", 1966

Sterilized deflated rubber bulbs were fastened to the side of Knudsen water-sampling bottles. These opened at the same time as the Knudsen bottles were triggered (Ad Hoc Working Committee on Methodology, 1966).

TOTAL COLIFORM BACTERIA

NHW and OWRC, 1965 and FWPCA, 1965, 1967 and 1968

Membrane filtration followed by incubation of the filter with M-Endo MF broth at 35°C for 20 hours (American Public Health Association, 1965).

FECAL COLIFORM BACTERIA

NHW, 1965 and FWPCA, 1965, 1967 and 1968

Membrane filtration followed by incubation of the filter with fecal coliform medium at 44.5°C for 24 hours (Geldreich *et al.*, 1965).

FECAL STREPTOCOCCAL BACTERIA

NHW, 1965

Membrane filtration followed by incubation of the filter with M-enterococcus agar medium at 35°C for 48 hours (American Public Health Association, 1965).

FWPCA, 1965, 1967 and 1968

Membrane filteration, and incubation of the filter with KF-streptococcus agar at 35°C for 48 hours (Federal Water Pollution Control Administration, 1966, 1967).

STANDARD PLATE COUNT AT 20 and 35°C

NHW, 1965

Part of the sample was mixed with tryptone glucose yeast agar, then incubated at 20°C for 48 hours, or at 35°C for 24 hours (American Public Health Association, 1965).

FWPCA, 1965

Membrane filtration followed by incubation of the filter with tryptone glucose yeast agar at 20°C for 48 hours, or at 35°C for 24 hours (Federal Water Pollution Control Administration, 1966, 1967).

PHYSICAL OBSERVATIONS

CURRENT VELOCITY

EMR

Method A - moored current meters. Instruments were moored on a taut vertical wire, between a submerged buoy and an anchor. A floating buoy and another anchor were located 600 to 1,200 feet away. The two anchors were connected by a ground line. This U-shaped mooring facilitated placement and retrieval of the instruments, and kept the instruments stationary during use. The instruments were Plessey Model MO21 and Geodyne Model A920. Precision and accuracy limitations were such that the true reading was given within ±1 or 2 cm/sec for speeds in the range 5 to 80 cm/sec, and ±010° for all directions. The instruments were recovered every two to six weeks, to replace magnetic tapes and batteries.

Method B - drogues. Various objects with large submerged areas, and with radar reflectors above the water, were tracked by radar from ships or boats.

Method C - drift objects. Slightly buoyant objects were released, and carried along by surface currents. Initial and final locations and times were noted.

FWPCA, 1963 to 1965

Current meters (Geodyne Model 100) were moored similar to EMR method A. They were recovered every 3 to 6 months. Bottom drifters were released and carried along by bottom currents. Initial and final locations and times were noted.

TEMPERATURE

EMR, M/V "Brandal" and "Theron"

Method A - oceanographic reversing thermometers. Oceanographic reversing thermometers (two on each sampling bottle) were lowered to the required depth, and turned over after five minutes. Each thermometer was read twice. Scale corrections and thermal expansion corrections were applied to the readings. A single mean value for each depth was reported in the final data record (U.S.N. Hydrographic Office, 1955).

Method B - bathythermograph. A bathythermograph was lowered to produce a graph of temperature versus depth (U.S.N. Hydrographic Office, 1955).

Method C - thermistor. A thermistor was towed at a depth near one metre and the water temperature recorded continuously while the ship was underway.

FWPCA, 1964 and 1965

Self recording thermographs were set at several midlake stations at depths of 10, 15, 22 and 30 metres and retrieved at 3 and/or 6 month intervals. Each thermograph was calibrated before and after use.

SEDIMENT ANALYSIS

Surface sediments were collected using a Franklin (Toronto) grab (Franklin and Anderson, 1961) or a Shipek bucket sampler (Kemp and Lewis, 1968). A few Lake Ontario samples collected at the mouth of the Niagara River, in 1966, were taken with a Petersen dredge. The samplers were lowered slowly to curtail disturbance of a loose surface ooze commonly present in muddy areas. The samplers recovered sediment (up to 12 centimetres depth in soft mud) from a single point on the lake bed. On hard clay, rock or sand bottoms, the samplers tended to scrape the lake bed and collect only the looser surface debris. Some sample loss probably occurred by washing through the jaws of the Franklin and Petersen grabs.

The sediment column, was sampled with Kullenberg piston corers fitted with plastic tubes of diameters ranging from 3.5 to 5.7 centimetres (Kullenberg, 1947). Gravity corers, consisting of weighted tubes up to 2 metres long, with a check valve in their upper ends, were used in the extensive reconnaissance of surficial sediment sequences. The Toronto gravity corer (Lewis, 1966) was used primarily in Lake Erie and an Alpine gravity corer (Lewis and McNeely, 1967) in Lake Ontario.

Surface sediment samples and cores were refrigerated during storage. As soon as possible, sub-samples were taken and analysed for organic matter and particle size distribution. For those sediments in which organic carbon and chlorophyll pigments are reported, the samples were refrigerated and freeze-dried almost immediately following collection.

POSTGLACIAL MUD THICKNESS

This feature was mapped acoustically throughout the basins. Thicknesses to the nearest 0.5 metres were read from echograms of a 14.25 KHZ sounder showing reflections from the mud surface and the sub-bottom surface of the underlying glacial deposits. The speed of sound in the mud was assumed to be similar to that in water, about 1.46 km/sec. Acoustically measured mud thicknesses correlated well with observed mud sections in piston core samples.

SEDIMENT PARTICLE SIZE

The distribution of particle diameters ranging from 1 micron to 2 millimetres or more was determined by combining results from different methods. Particles coarser than 63 microns were sieved through a screen nest, having ½ ϕ aperture intervals (diameter in ϕ units = $-\log_2$ (diameter in millimetres)). Weight percentages were calculated as described by Krumbein and Pettijohn (1938). The size distribution of the fine-grained fraction was measured by sedimentation methods, following dispersion of the sediment in 0.5 percent solution of Calgon or sodium hexametaphosphate. The suspension density was monitored with settling time using either the hydrometer method (Lambe, 1951; American Society for Testing and Materials, 1964; Lewis, 1966) or the pipet method (Krumbein and Pettijohn, 1938). Variations of mean particle diameter over each lake as shown in the sedimentology section of this report were largely based on the combined results of sieve and hydrometer analysis. The reported mean diameter of the sediment size distribution was computed from the cumulative frequency curves according to the equation:

$$M = \frac{\phi 84 + \phi 50 + \phi 16}{3.0}$$

where $\phi 84$, $\phi 50$ and $\phi 16$ are phi diameters of the 84th, 50th and 16th percentiles, respectively. A standard deviation of 0.035 was calculated for this parameter, based on replicate measurements of the same sample by the pipet and sieve methods.

MINERALOGY

Mineral identification of fine-grained sediment (clay and fine silt sizes) was accomplished with powder x-ray diffraction techniques using a Philips or similar diffractometer (Brown, 1961). Oriented mounts of the sediment powder were prepared following a procedure similar to that of Mallory and Kerr (1961) involving dispersion in distilled water, and sedimentation onto glass slides.

The constituent termed "clay mineral content" was computed from chemical measurements of some other constituents, using methods adapted from Trostell and Wynne (1940). Quartz was determined independently. The three results were subtracted from the total sediment amount. The clay mineral content determined by this method actually includes all components in the sediment other than quartz, feldspar, zircon, carbonate, and organic matter.

REDOX POTENTIAL AND HYDROGEN ION CONCENTRATION

Redox potential was measured at several levels in the sediment, down to 5 centimetres depth, immediately after recovering the Shipek bucket sample. The bucket was placed in a stand so that the sediment surface was horizontal. Combination glass/Ag Cl and platinum/Ag Cl electrodes were inserted at predetermined depths and clamped securely. Readings of pH were taken between 30 and 60 seconds after insertion with a Metrohm E 208A meter. Eh potentials were read on the same meter after a 10 minute stabilization period. Sample temperatures were recorded at the same time.

ORGANIC MATTER (LAKE ONTARIO)

The organic matter of bottom sediments in western Lake Ontario was determined from sub-samples taken from refrigerated, homogenized Franklin grab samples. Eastern Lake Ontario sediments were taken from the upper centimetre of gravity cores and were similarly analysed. The oxidizable organic content was measured by a wet dichromate oxidation method, the modified Walkley-Black method (Jackson, 1958). It was assumed that 70 percent of the carbon present was oxidized by the chromic acid, and that the total carbon comprised 58 percent of the organic matter. Observed values of oxidized material were increased by these factors and reported as percent organic matter in dry weight of sediment. The coefficient of variation (the ratio of the standard deviation to the mean value) varied from 0.6 percent to 6.7 percent on samples containing 25.0 and 0.5 percent oxidizable organic matter, respectively.

ORGANIC CARBON

Total carbon (carbonate + organic) was measured by heating the freeze-dried sample to about 1,300°C in a Leco induction furnace carbon analyser. Organic carbon was measured in the same furnace after carbonate removal in sulphurous acid at room temperature (Rittenberg *et al.*, 1963; Shaw, 1939). Organic carbon was reported for selected sediment samples along the axes of Lakes Erie and Ontario.

CHLOROPHYLL PIGMENTS

Pigments were extracted from the dried sediments in cold 80 percent acetone under 5 minutes of ultrosonic probe treatment. The absorbance was measured at 536, 645, 655, 662 and 666 millimicrons with a Bausch and Lomb Spectronic spectrophotometer. The method and calculations are based on the procedures of Vernon (1960). The coefficient of variation was 2 percent, except at low chlorophyll or pheophytin concentrations of about 5 ppm, where the coefficient of variation was 20 percent.

NITRATE, PHOSPHATE, AMMONIA

Nitrate, phosphate and ammonia were extracted from freeze-dried sediments by electrodialysis. Nitrate and ammonia were determined by the rapid methods given by Bear (1964). The extracted orthophosphate was measured colorimetrically after ascorbic acid reduction (Fogg and Wilkinson, 1958).

SULPHIDES

FWPCA (LEBO)

Sulphides were separated by distillation into zinc acetate. The resultant zinc sulphide was reacted with N, N-Dimethye, P-phenylenediamine in sulphuric acid and ferric chloride to form methylene blue. The methylene blue was measured spectrophotometrically at 650 millimicrons.

PHYTOPLANKTON METHODS

General

Phytoplankton counts are reported in a variety of ways, as cells, colonies or clumps, in areal units or in volumetric units. Because of the size ranges for different species, only volumetric measurements are directly proportional to biomass. Identification is usually made only to the generic level. Counts are generally reliable to within 5 to 20 percent of stated values.

FWPCA

Samples (usually 2 litres in volume) were collected with a polyvinyl chloride (PVC) sampler from stated depths (surface, thermocline and bottom in the case of Lake Ontario) and analyzed separately. The samples were preserved by the addition of formalin (37 percent formaldehyde) to yield a 3 percent solution of formaldahyde on mixing with the sample. Prior to counting, the water sample was repeatedly shaken by inversion and an aliquot transferred by means of a dropper to a one millilitre Sedgwick-Rafter counting chamber as quickly as possible. The contents were allowed to settle for 15 minutes. Microscopic analyses were made using 10X oculars and a 20X objective, one of the oculars being fitted with a Whipple ocular micrometer. Two strips were normally counted, each one Whipple field wide. When the sample was sparsely populated, 4 to 8 strips were counted and when dense, only one. The clump count method was used for enumeration. Colonies, filaments and isolated cells were counted as single units. Identification was made at 200X magnification. Forms not identifiable at this magnification were simply referred to as unidentified members of a given group. Results were calculated by multiplying by a factor appropriate to the number of strips counted (American Public Health Association, 1965). Permanent slides of diatoms were prepared and the remainder of the sample discarded.

OWRC

Samples from municipal water treatment plants were collected in 40 ounce bottles and concentrated using the Sedgwick-Rafter sand filtration technique (American Public Health Association, 1965). A predetermined volume of the concentrate was examined in a one millilitre Sedgwick-Rafter counting cell as previously described (American Public Health Association, 1965). All algae were identified to the generic level with results expressed as areal standard units (asu). One asu is equivalent to 400 square microns.

Samples from offshore waters were collected by two different methods. Up to August 1, 1967, equal volumes of water (collected by a 40 ounce water bottle) from 1.5 metres and 4X Secchi depth were combined and counted as described above for samples from water treatment plants. After August 1, 1967, all samples were obtained by lowering a 40 ounce bottle provided with a restricted inlet to 4X Secchi depth. The bottle was lowered and raised by prior trial at such a rate that it just filled completely as it reached the water surface on ascent.

Samples were preserved by addition of a 5 percent solution of 5 to 10 percent methanol in formalin (37 percent formaldehyde). All phytoplankton samples were retained for future reference. Permanent slides of diatoms were made by mounting in either Hyrax or Mikrops mounting media.

FRB

Samples were collected with a PVC water sampler from stated depths, and preserved by the addition of 5 percent Lugol's solution.

CHLOROPHYLL METHODS

FWPCA and OWRC

The method of Richards and Thompson (1952) as modified by Creitz and Richards (1955) was used for determination of chlorophyll. Millipore HA filters were used for the filtration of 250 to 1,000 millilitres of water depending on the density of phytoplankton. Filters were refrigerated and stored in a desiccator in the dark until extracted with 15 millilitres of 90 percent acetone in a centrifuge tube. FWPCA used a Vortex Junior Mixer to facilitate initial extraction. After 18 to 24 hours extraction in the dark, the samples were centrifuged and extracts transferred to a cuvette. Optical density was determined at 665, 645, and 630 millimicrons using a Beckman Model B or Model DU spectrophotometer. The formulas used for determination of chlorophylls a, b, and c in the extract were (Creitz and Richards, 1955):

Chlorophyll a (mg/l) $15.6\ D_{665} - 2.0\ D_{645} - 0.8\ D_{630}$

Chlorophyll b (mg/l) $25.4\ D_{645} - 4.4\ D_{665} - 10.3\ D_{630}$

Chlorophyll c (mg/l) $109\ D_{630} - 12.5\ D_{665} - 28.7\ D_{645}$

Chlorophyll values in mg/m^3 of water were then obtained as follows:

$$\frac{\text{ml of extract}}{\text{litres filtered}} \times \frac{1}{\text{light path of cuvette (cm)}}$$

Results were expressed as chlorophyll (a + b) or as chlorophyll a. Chlorophyll c values were usually not calculated because of the high error involved.

FRB

The *in vivo* fluorometric method of Lorenzen (1966) was used for chlorophyll determination, with standardization through periodic determinations of chlorophyll a using the method of Creitz and Richards (1955). Modifications of Lorenzen's procedure included the use of a larger recorder, and warming of the inflowing water to avoid condensation of moisture on the surface of the flow-through cell.

ZOOPLANKTON METHODS

General

Zooplankton can be collected with a variety of devices ranging from traps that open at a particular depth enclosing a standard volume of water, to metered or unmetered nets towed through the water either vertically or horizontally. Regardless of the sampling apparatus all measurements are relative only. The efficiency of net sampling varies with the mesh size, the rate at which the net is hauled through the water, and the degree of clogging from concentrations of algae and zooplankton.

FWPCA

Collections were made with a Wisconsin-type plankton net (50 centimetres in diameter, with a 6 foot length of #20 bolting cloth) and preserved in 3 percent formaldehyde. Vertical hauls were made from 3 metres above bottom to the water surface during daylight hours. The samples taken have not yet been analyzed in detail, but are being retained for future reference.

OWRC

Collections were made with a Wisconsin-type plankton net (12 centimetres in diameter, with a 23 inch length of #20 mesh Nylon bolting cloth). The samples were collected by vertical hauls from 7 metres depth to the water surface, raising the net slowly by hand. The collections were made during daylight hours only. The fraction of the sample counted varied from 1/15 to 2/3 depending on the numbers involved. Duplicate counts using a Sedgwick-Rafter counting cell were usually made for about 10 percent of the samples. Species identifications were made at 400X magnification. Samples were preserved in 5 percent formalin and were retained for future reference.

FRB

Collections were made with a Wisconsin-type plankton net (25 centimetres in diameter, 70 centimetres length of nylon bolting cloth with a mesh opening of 70 microns). The net was hauled vertically from 50 metres depth to the surface at a rate of 0.3 to 0.5 m/sec. For stations shallower than 50 metres depth, the net was hauled from just above bottom to the surface. A minimum of 200 specimens per haul was counted using a Sedgwick-Rafter counting cell, representing 1/100 to 1/500 of the total number of specimens per haul. Samples were preserved in 8 percent formalin with representative samples retained permanently on file at the FRB Freshwater Institute. Samples were collected anytime during the day or night that the ship was on station. Tests have shown that an average of 90 percent of the total zooplanktonic populations (by number) occurs in the uppermost 50 metres. *Limnocalanus macrurus* is not adequately sampled by this procedure.

BENTHOS METHODS

General

No single dredge is effective for all substrates in sampling the benthic population. There are also marked differences in sampling efficiency for different types of dredges. Only samples taken with the same dredge in similar types of substrate can be compared on a quantitative basis.

FWPCA

All collections were made with a Petersen dredge concentrated through a 30 mesh/inch sieve and sorted according to the procedures described by the American Public Health Association (1965). The preservative consisted of 40 millilitres of formalin mixed with 60 millilitres of 70 percent ethanol. Phloxine B or Rose Bengal were used as stains. Data were expressed in terms of the number of organisms per square metre. Samples were either retained by FWPCA or sent to the Ohio State Museum for future reference.

OWRC

Collections in 1966 were made with a Petersen dredge, approximately ten inches by ten and a half inches. Collections in 1967 were made with a Ponar dredge, approximately nine inches by nine inches. Samples were sorted through a 24 mesh sieve (0.65 mm aperture) and preserved in 95 percent ethanol. All samples were retained by OWRC. Data were expressed in terms of the number of organisms per square metre.

GLI and FRB

Samples were collected with a Franklin dredge, kept cool until the termination of each cruise and sorted in a laboratory in a column bounded by two sieves through which water was allowed to flow. Subsequent tests revealed that the operation of this sieving device resulted in losses of specimens, probably due to maceration between sediment particles. Further details on the number and times of cruises, and the sampling stations, are given in Brinkhurst *et al.* (1968).

SESTON METHODS

FWPCA

Gravimetric determinations of seston were conducted to provide a gross estimate of standing crop. Samples for organic seston determinations were collected at the same depths as for phytoplankton by the membrane filter technique. A two-litre plastic bottle was filled and 60 millilitres of Lugol's preservative or formalin was added.

Crucibles and covers were washed in a detergent solution, rinsed in tap water, and placed in a 30 to 40 percent nitric acid solution for at least two hours. They were then removed and immersed in distilled water for 5 to 10 minutes and placed in a pan until the excess water evaporated.

The crucibles and covers were then placed in a muffle furnace preheated to 600°C for 30 minutes, removed, allowed to cool at room temperature for several minutes, and placed in a desiccator.

After removal from the desiccator, each crucible and its corresponding numbered cover were weighed together on an analytical balance, the cover being inverted on top of the crucible, and the weight recorded. A dried HA 0.45 micron membrane filter was placed in the inverted cover and the crucible cover and filter weighed. This weight was recorded as the tare weight.

Aliquots were passed through the weighed filters and each filter returned to the crucible from which it was taken and the cover replaced. The crucibles were then dried in the drying oven at 100°C for one hour. They were then removed, placed in a desiccator for at least one hour, weighed again, and the weight recorded as the total dry weight. The difference between the tare weight and dry weight was the sample residue weight.

The crucibles, filters, and covers were then placed in a muffle furnace at a temperature of 600°C for 30 minutes, removed and after several minutes, placed in a desiccator for at least one hour, weighed, and the weight recorded as ashed weight. The difference between the ashed weight and the crucible and cover weight was the weight of the non-organic material in the sample. The difference between the dry residue weight and the non-organic material was the weight of the organic material. This figure was converted to either milligrams of seston per cubic metre or milligrams per litre. The measurement is similar to that for volatile and fixed solids.

METHOD FOR DDE RESIDUES IN FISH

OWRC, 1966 and 1967

The fresh fish were kept on ice until they could be frozen for extended storage. In preparing the fish for analyses, they were thawed and the specific tissued dissected out and homogenized in a food blender. In the case of whole fish composites, the fish were ground in a meat grinder.

In the saponification step of the analyses, a 10 gram homogenized sample was boiled for 30 minutes with 40 millilitres of 20 percent potassium hydroxide. In the saponification step, the tissue was converted to a water-soluble liquid and any DDT present was converted to DDE. Any DDE present remained unchanged. The DDE was extracted from the saponified tissue using 3 x 15 millilitres portions of hexane in a 125 millilitre separatory funnel. The hexane was cleaned by using column chromatography on florosil. An Aerograph 1520 gas chromatograph was used for the analysis. All measurements were calculated in terms of mg/kg DDE per unit fresh weight of tissue.

LAKE ERIE MATERIAL BALANCE

LAKE HURON OUTPUT

The method used for calculating loadings was based on data of average constituent concentration determined on IJC Range SR 13.7 during the sampling period of May to October, 1967. The loadings thus calculated resulted in the following concentrations when adjusted to the 1900-1967 average flow of the St. Clair River of 177,000 cfs: total-N 380 μg/l, total-P 12.5 μg/l, Cl 5.7 mg/l, dissolved solids 136 mg/l.

Constituent	Data Collection Agency	Data Year
N - inorg.	OWRC	1967
N - org.	FWPCA	1967
P	OWRC	1967
Cl	OWRC	-
Dissolved solids	FWPCA	1967

DETROIT RIVER OUTPUT

Calculated loadings were based on data of average constituent concentration determined on IJC Range DT 3.9 during two sampling periods (April to October in 1966 and 1967). The loadings thus calculated resulted in the following concentrations when adjusted to the 1900-1967 average flow of the Detroit River of 178,000 cfs: total-N 720 μg/l, total-P 100 μg/l, Cl 18.8 mg/l, dissolved solids 166 mg/l.

Constituent	Data Collection Agency	Data Year
N - inorg.	OWRC	1966 and 1967
N - org.	FWPCA	1967
P	OWRC and FWPCA	1966 and 1967
Cl	OWRC	1966 and 1967
Dissolved solids	FWPCA	1967

LAKE ERIE INPUTS

Includes municipal and industrial point sources, municipal, industrial and land drainage tributary sources and natural sources.

Point Sources

Municipal

Municipal sources were sampled on a monthly basis during 1967 in both Ontario and the United States. Loadings were then calculated using measured concentrations and metered average annual flows.

Industrial

Industrial loadings in Ontario were based, in most cases, on four samples and flow measurements during 1967 and supplemented by past data and company records.

Tributaries

Municipal

Municipal nutrient loads in Ontario were based on urban population and per capita annual contributions of 3 lbs. P (MacKenthen, 1968) and 9 lbs. N (Vollenweider, 1968).

Industrial

Industrial loads are based, in most instances, on two annual measurements of concentrations and metered annual flow, in both the United States and Ontario.

Land Drainage

Land drainage is the total tributary load minus the municipal and industrial loads. The tributary loads were based on the periods of 1965 to 1967 for the United States and the period 1964-1965 (October 1 to September 30), and 1965-1966, with a frequency of 8-12 times per year for Ontario and 26 times per year for the United States. Loadings were calculated using concentrations and daily flow values at the time of sampling.

Natural sources represent an estimated nitrogen contribution of 5 lbs/acre/year to the lake surface through precipitation. Matheson (1951) measured nitrogen in precipitation as averaging 5.8 lbs/acre/year. McKee (1962) reports values equivalent to 1.8 to 8.9 lbs/acre/year, with an average of about 5 lbs/acre/year. Therefore, a value of 5.0 lbs/acre/year was taken as being representative of the Great Lakes Region.

TOTAL OUTPUT

This includes the output to the Niagara River, the output to the Welland Canal, and in the case of nitrogen and phosphorus, the output in fish catch, estimated at 55 tons of phosphorus and 690 tons of nitrogen.

LAKE ERIE OUTPUT TO UPPER NIAGARA RIVER

The loads were calculated using the average concentrations measured at Eastern Lake Erie IJC Range P-1W plus inputs along the United States shore between point "P" to a point just below the Buffalo Creek. The loadings thus obtained resulted in the following concentrations when adjusted to 1900-1967 average flow of the upper Niagara River of 194,000 cfs: total-N 420 μg/l, total-P 20 μg/l, Cl 26 mg/l, dissolved solids 191 mg/l.

Constituent	Data Collection Agency	Data Year
N - total	FWPCA and OWRC	1963 and 1964 1967
P	OWRC	1966 and 1967
Cl	OWRC	1966 and 1967
Dissolved solids	FWPCA	1963 and 1964

LAKE ERIE OUTPUT TO WELLAND CANAL

The load calculations were based on average concentration over two sampling periods (April to October) 1966-1967 at two monitor stations adjacent to the canal entrance (one and two miles) and the average of the 1966-1967 flow into the canal of 7,485 cfs.

Constituent	Data Collection Agency	Data Year
N - total	OWRC	1966 and 1967
P	OWRC	1966 and 1967
Cl	OWRC	1966 and 1967
Dissolved solids	OWRC	1966 and 1967

ANNUAL INPUT OF TOTAL PHOSPHORUS PROJECTED TO 1986

LAKE HURON

It was assumed that the Lake Huron phosphorus concentration will not be permitted to exceed 15 µg/l. The projected input to the St. Clair River thus would not exceed 2,600 tons/year.

MUNICIPAL INPUTS

Municipal inputs are based on projected urban population and an annual per capita contribution of 3.5 lbs. P - as raw sewage. The population projection is based on population trends and anticipated economic growth. Phosphorus contribution of 3.5 lbs/person/year is based on current United States loadings and anticipated Canadian loadings. This is considered a conservative value in view of past trends in annual per capita consumption of phosphates in detergents.

INDUSTRIAL INPUTS

Industrial growth was estimated in part on past economic performance and on a knowledge of planned and proposed industrial expansion, particularly in development of thermal power. The real economic growth rate in Ontario has been in the order of 4 percent per year. By 1986 this is expected to compound to a factor of about 2.5 times. Industrial projections for the United States were based on past trends of employment for each water use industry. The resultant water use indexes of growth were developed for Standard Industrial Classification categories and also reflect productivity and water re-use factors.

LAND DRAINAGE

By 1986 the amount of phosphorus contributed by land drainage is expected to increase 20 percent. This is based on such factors as past trends in fertilizer use, replacement of forest cover by farm crops and increased soil erosion.

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